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Effects of Millisecond-Delay Intervals on Vibration and Airblast From Surface Coal Mine Blasting

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UNITED STATES DEPARTMENT OF THE INTERIOR

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Donald Paul Hodel, Secretary

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Robert C. Horton, Director

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT			
dB	decibel	lb/yr	pound per year
ft	foot	mm	millimeter
ft/lb	foot per pound	ms	millisecond
Hz	hertz	ms/ft	millisecond per foot
in	inch	pct	percent
in/s	inch per second	s	second
lb	pound		

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EFFECTS OF MILLISECOND-DELAY INTERVALS ON VIBRATION AND AIRBLAST FROM SURFACE COAL MINE BLASTING

By John W. Kopp[1] and David E. Siskind[2]

ABSTRACT

A major concern with blasting at surface mines is generation of ground vibrations and airblast and their effects on nearby residences. This Bureau of Mines report looks at the use of millisecond delays in blast design and their effect on the resulting ground vibrations and airblast. A total of 52 production blasts were instrumented and monitored at a surface coal mine in southern Indiana. Arrays of seismographs were used to gather time histories of vibrations and airblast. The data were analyzed for peak values of vibration and airblast and for frequency content. Various delay intervals were used within and between rows of blastholes. Delay intervals within rows were 17 and 42 ms, and those between rows ranged from 30 to 100 ms; these intervals are equivalent to 0.5 and 1.3 ms/ft within rows and 1.2 to 4.3 ms/ft between rows. Subsonic delay intervals within rows reduced airblast by 6 dB. Large delay intervals between rows reduced the amplitude of ground vibrations; their frequency depended primarily upon the geology of the mine site.

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INTRODUCTION

Explosives are widely employed for rock fragmentation by the mining, quarrying, and construction industries, which use approximately 4 billion lb/yr in the United States. Three major areas of concern to blasters are productivity, environment, and occupational safety. Productivity means efficient and effective fragmentation with uniform and appropriate-sized material and proper displacement. Environmental problems are those that can affect neighbors and include ground vibration, airblast, flyrock, dust, and fumes. Safety considerations include explosive handling and blasting procedures as they could affect the workers.

The scientific analysis of blast designs has become of interest as the industries involved attempt to tailor blasts to specific purposes or problems. In the past, blast designs were determined by trial and error. With the mining of lower grade materials and increasing proximity of centers of population to areas of active mining, the mining companies, explosives suppliers, and supporting consultants are taking a more active design role. They are participating in the development and application of improved techniques and devices for positive control of the blasting results and their potential impacts.

A great improvement in blasting technology occurred with the application of delayed blasting in the 1940's and 1950's. Although the technique was originally developed to provide improved fragmentation through control of lateral and forward blast relief, the time spreading of the blast energy also results in lower level peak ground vibrations and airblasts. Bureau of Mines research published in 1963 (1)[3] demonstrated the powerful effect of millisecond-delayed blasts in reducing ground vibration generation. The authors of that study stated that peak vibration levels (particle velocities) correlated better with the amount of explosive per delay than with the total charge weight. In other words, within their experimental parameters of three delays (9, 17, and 34 ms) and three amounts of delayed holes per blast (3, 7, and 15), the vibration amplitudes were independent of both the delay length and the number of holes. From this Bureau research have come the widely adopted scaled-distance prediction schemes for both ground vibrations and airblast (2).

Starting in the mid 1970's, a large amount of new information was developed on explosive performance and impact. Research by the Bureau of Mines (3-4) and others (5-7) demonstrated the importance of vibration frequency as well as amplitude to the impact on neighboring residential structures and also to annoyance potential. Some effects of delay intervals on wave frequency character were also observed, particularly for airblast (8).

During the same period, new technology created increased blast design opportunities and versatility. In particular, the electronic 10-circuit sequential blasting machine in conjunction with down-hole delays allowed a greatly increased number of independent delay intervals and the possibility of improved delay accuracy. A study by Winzer (9) had shown the inaccuracies of existing pyrotechnic delay blast initiators and the possible adverse effects on rock fragmentation, displacement, and environmental impacts. Winzer's follow-on research described the most serious problem of holes firing out of sequence, leading to violent cratering, excessive backbreak, and above-normal ground vibrations (10-11). Even minor crowding of adjacent holes seriously reduced burden relief. The direct consequences were erratic and unstable highwalls, excessive vibration, airblast, and flyrock, and irregular fragmentation including boxcar-sized boulders (12-14).

Although the recent research efforts on ground vibrations and airblast response identified salient wave characteristics governing impact magnitudes, they do not describe methods to influence such

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

impacts. Some new results do exist, e.g., the Bureau-sponsored research by Wiss on design of surface coal mine production blasts and resulting vibrations and airblast (15). Similarly, some of Winzer's and other recent and ongoing stone quarry studies promise to provide insight into blast effect fundamentals (10-14).

This report describes Bureau research primarily on the generation, but also on the propagation, of ground vibration and airblast from carefully characterized blasts with large-diameter blastholes. Both standard highwall production blasts and a special improved-precision initiation version were studied at a surface coal mine in southern Indiana in an attempt to answer the following questions:

1. How are the vibration and airblast generated as a function of delay intervals, both nominal (designed) and actual?

2. How can the frequency and amplitude of both vibration and airblast be influenced by initiation delay control?

3. How do these vibrations propagate and change character as functions of distance and geometric relationship between a given direction and the highwall orientation?

The answers to these questions gained through studies of this type will provide blasters with the tools to modify or adjust blast design for desired impacts along with information on the productivity and practicality of such changes. With the rapid growth in blasting technology, future blasters will need an increased control over explosive performance and application through blast design.

ACKNOWLEDGMENTS

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PREVIOUS AND RELATED RESEARCH

The Bureau conducted research on vibrations from quarry blasting during the 1960's. As part of this research, the Bureau studied 19 blasts at a limestone quarry in Iowa. Both instantaneous and millisecond-delayed blasts were studied, using 9-, 17-, and 34-ms delays (1). Arrays of particle velocity gages were used to record the vibrations from the shots. Distances ranged from 150 to 3,000 ft. Six-inch-diameter blast holes with 200 lb of explosive in each were used in the experiments. The blasts ranged in size from 1 to 15 holes.

The study concluded that the particle velocity was dependent on the distance from the blast and the charge weight per delay interval for the three delays examined and could be predicted by the equation

$$V = KW^{b}D^{-n},$$

where V, W, and D are particle velocity, charge weight per delay, and distance, respectively, b is the scaling exponent for charge weight, n is the regression exponent, and K is a site-dependent constant. The authors found that vibration levels were independent of the length of delay used or the total weight of explosives in the shot.

Some work has been carried out on the relationship of delay interval and burden and spacing to fragmentation. Bergmann (16) did model blasting tests on Vermont granite blocks to study fragmentation. Both square and rectangular patterns were tested. Bergmann concluded that a rectangular pattern with spacing equal to twice the burden was best for fragmentation. He also recommended that a minimum delay interval of 1 ms per foot of burden should be used for adjacent holes for best fragmentation results.

Andrews (12) has made recommendations to reduce airblast, based on work done at a limestone quarry in the Eastern United States. The airblast intensity was influenced by the average rate of blast propagation along the face of the shot. When the rate of propagation matched or exceeded the velocity of sound in air, a strong airblast was produced in line with and forward of the face. This can be eliminated by making the delay interval between holes along the free face greater than 1 ms/ft.

More recent work by Andrews (13) has revised his earlier findings and those of Bergmann. He found that poor fragmentation can result if the delay interval between holes in a row is greater than 5 ms per foot of burden. This is apparently caused by the movement of the burden before the stress wave from the next hole can cause further fragmentation. Best results are obtained when the delay interval between holes within a row is between 1 and 5 ms/ft. It was also found that the delay time between rows should be two to three times the delay interval between holes in a row. This allows sufficient time for the burden to move, giving the next row's burden relief for movement.

Winzer (9-10, 17) of Martin-Marietta Laboratories has studied the relationship of blast design to fragmentation. His work has been primarily conducted through analysis of high-speed films of the shot. He found that the firing times of millisecond-series-delay caps varied greatly from the firing times given by the manufacturers and often resulted in some holes going off out of sequence during a blast.

Analysis of actual initiation times of a 55-hole shot allowed calculation of burden and spacing firing times for various areas of the blast. Based on this, Winzer (10) recommended using 3.4 ms/ft relief for holes within a row and 7.7 ms/ft relief for burden between rows, in order to minimize venting of stemming and flyrock.

Using this criterion, Winzer (17) conducted tests at several quarries. Delays were used that allowed 3.8 to 4.2 ms/ft between holes within a row and a burden relief of 10 ms/ft between echelons. These tests resulted in better fragmentation than previous blasting that utilized shorter delays. Experimentation also showed that for shots with more than 5 echelons, it is necessary to increase the delays between echelons that are deeper in the shot to get adequate burden relief. This was accomplished using a sequential timer with variable intervals between circuits.

Oriard (18) tested different delay intervals between holes in one-row shots at Anaconda's Berkeley Pit. He used delay intervals of 5, 9, and 17 ms. The spacing of holes was 22 ft, giving a spacing relief of less than 1 ms/ft. The shots utilizing 5- and 9-ms delays showed little difference in vibration levels. Shots using 17-ms delays and greater showed lower vibration levels than the shorter delays, but this may not have been statistically significant. The upper bounds for vibration levels were nearly identical for all delays.

The Bureau contracted with Wiss, Janney, Elstner, and Associates (15) to identify factors of blast design that affect ground vibrations and airblast levels. Wiss studied 111 blasts at 4 surface mines and an additional 155 scale model tests at a quarry. The factors studied were charge weight per delay, length of delay, stemming, charge weight per blast, directional effects, burden and spacing, charge depth, angle of borehole, covering of detonating cord, charge length and diameter, surface terrain, wind conditions, and type of overburden.

Wiss recommended that, to reduce airblast and ground vibrations, the following should be done: (1) Minimize the amount of explosive per delay period, (2) avoid short delay periods--use 17-ms delays or greater between holes, and (3) select blasthole spacing and delay intervals to avoid reinforcement of the blast wave. Additionally, airblast can be reduced by the following: (1) Maximize the charge depth of burial, (2) use coarse angular stemming material, (3) cover detonating cord with 3 in or more of material, and (4) avoid unfavorable wind conditions.

Wiss also found that direction of initiation caused a difference in levels of vibration and airblast. However, for this test only horizontal holes were used, a condition not typical of most surface blasting. Vibration levels were highest in the direction of initiation and lowest away from the direction of initiation.

The Bureau has done further work to evalute the effect of initiation direction using vertical blastholes and multirow shots. The results of this study are presented in this report.

Previous work done by Winzer, Wiss, and others showed that blasts designed to improve fragmentation also tend to reduce vibrations and airblast.

EXPERIMENTAL DESIGN

INSTRUMENTATION AND MEASUREMENT TECHNIQUES

Airblast and ground vibrations were measured with 12 Dallas ST-4[4] self-triggered seismographs. These seismographs recorded three components of ground motion and the airblast overpressure on standard cassette audiotapes. The tape recorder for each machine was automatically activated when the ground vibration reached a predetermined level, selectable from 0.05 to 0.25 in/s peak particle velocity. The recorder uses an FM format with a dynamic range of 38 dB and a frequency response from 0 to 200 Hz. The circuitry includes a 400-ms delay in order to capture the entire seismic wave.

The frequency range of the transducers used for ground vibration was 1 to 200 Hz. The maximum amplitude that could be recorded was 4 in/s. For low-level signals, an alternate range could be selected with a maximum amplitude to 1 in/s. Four seismographs were modified to be four times more sensitive, maximum values becoming 1 and 0.25 in/s. This was accomplished by changing the values of resistors on the signal amplifiers. The instrument is further discussed by Stagg (19).

The airblast channel used a 1-1/8-in ceramic microphone. The frequency response of the system was 5 to 200 Hz, with a maximum peak overpressure of 137 dB. The microphones were modified to give a lower end frequency response of 0.2 Hz. Stachura discusses instrument characteristics further (8) and gives additional information about the modifications (20).

The blasts were also monitored using a 16-mm high-speed cinecamera. The rotating-prism camera was capable of speeds in excess of 8,000 frames per second, but a rate of 1,000 frames per second was sufficient for this study. This allowed computation of the firing time for each delay to the nearest millisecond. The firing system used was Nonel with surface delays. Nonel tubing was also tied into the delay initiators in order to provide a flash signal for the camera to record. Ground movement and rock trajectories were not analyzed because only one camera was used and picture quality was not good enough.

TEST SITE

The project test site was a surface coal mine in southern Indiana (fig. 1). The mine utilizes two large draglines to remove 50 to 100 ft of overburden from a 4- to 5-ft coal seam. The overburden is primarily shale with some sandstone intermixed. An east-west geologic cross section is shown in figure 2. The shale requires blasting to facilitate digging by the draglines. Blasting is accomplished using 12-1/4-in holes drilled on a 30-ft-square pattern and shot en echelon into a buffer. The terrain is flat to gently rolling hills. The layout of the pit is not influenced by topography and is in a north-south direction about 3 miles long. The movement of mining is toward the west.

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

FIGURE 1. - Blasting operation at surface coal mine.

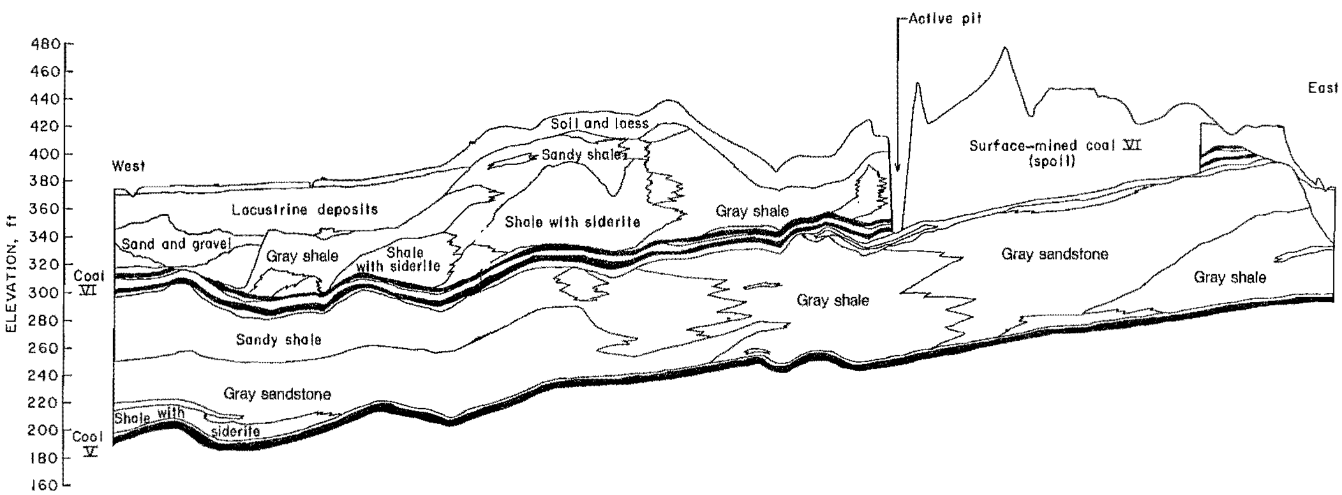

FIGURE 2. - Geologic cross section of mining area.

TEST PROCEDURE

This series of tests had two phases. First, to determine if orientation of the shot affected vibration levels, seismograph arrays were established in four directions from the shot. Each array line used three instruments, located at distances of 300 to 500 ft, 1,000 to 1,500 ft, and about 3,000 to 5,000 ft. A typical seismograph layout in relation to the pit is shown in figure 3. The

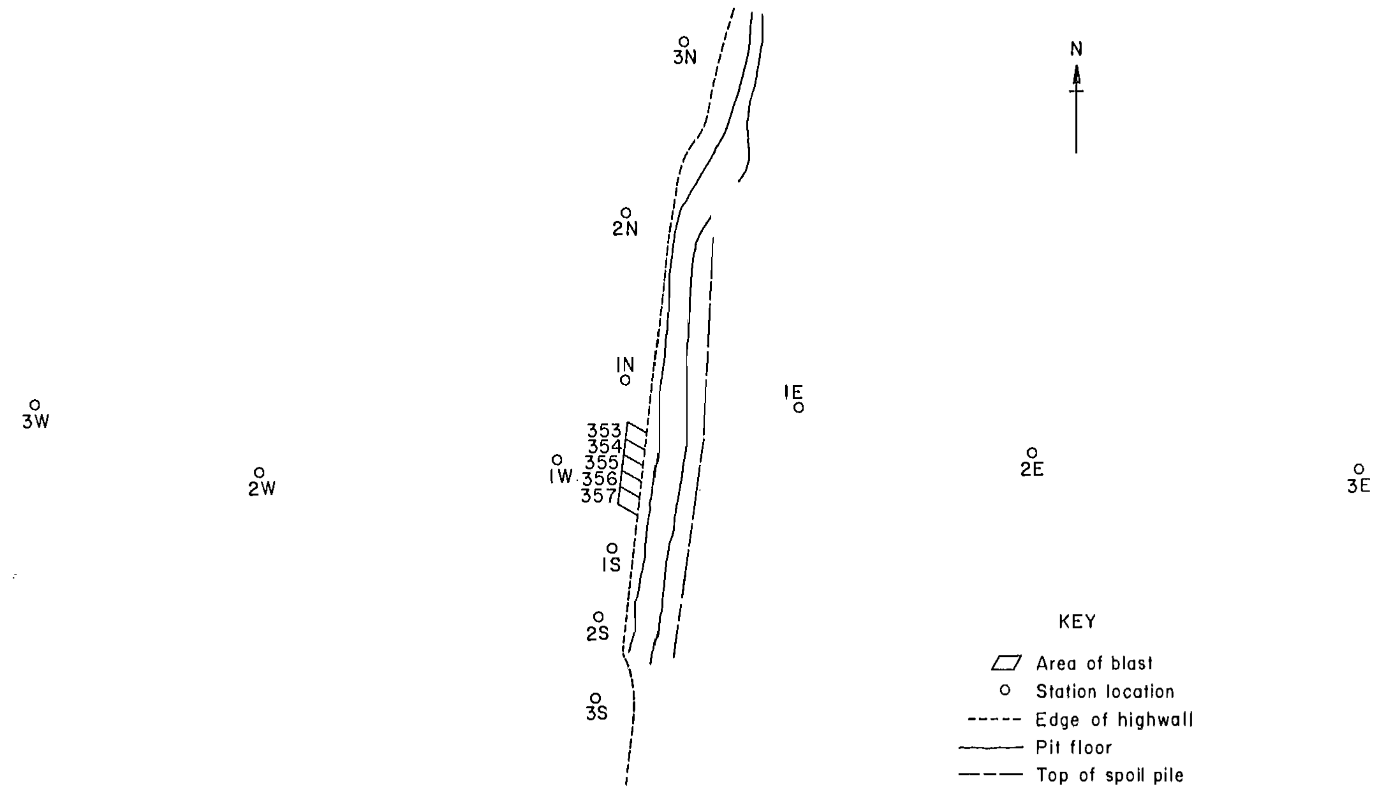

FIGURE 3. - Map of test area showing seismograph locations.

complete waveforms of vibration and airblast were recorded at each station. From this, the frequency spectra and peak particle velocities and airblast could be determined. Peak particle velocities were plotted as propagation plots of amplitude versus scaled distance for each array direction. A least-squares fit of the regression line was determined for each set of data. A one-way analysis of variance test was then performed on the data sets to determine if the blast parameter under study was significant. The test involves two steps. First, the question is asked, can the data be pooled, i.e., represented by one regression line? If so, then the variable under study is not significant. If not, then can the data sets be represented by one average slope? If they can, then differences caused by the variable can be accounted for by differences in the intercept value. These two hypotheses are tested by calculating the appropriate F-statistic. This is discussed further by Wiss (15).

The second phase of testing varied the delay intervals between holes and rows. Airblast and vibration measurements were made as before with seismographs deployed in arrays in the four directions. Delay intervals used were 17 and 42 ms between holes in an echelon and 30, 42, 60, 75, and 100 ms between echelons. Standard production shots used 17 ms between holes in an echelon and 42 ms between echelons. The Nonel Primadet system was used for these delays. Delay intervals between rows for shots 37 to 52 were obtained by using electric caps, all of one period, with a sequential blasting machine. A typical shot pattern is shown in figure 4. A high-speed camera was used to determine actual firing times for each hole. Propagation plots were made of the airblast and vibration data. Again, analysis of variance tests as described above were utilized to determine if a significant difference existed in vibration levels for the different delay intervals.

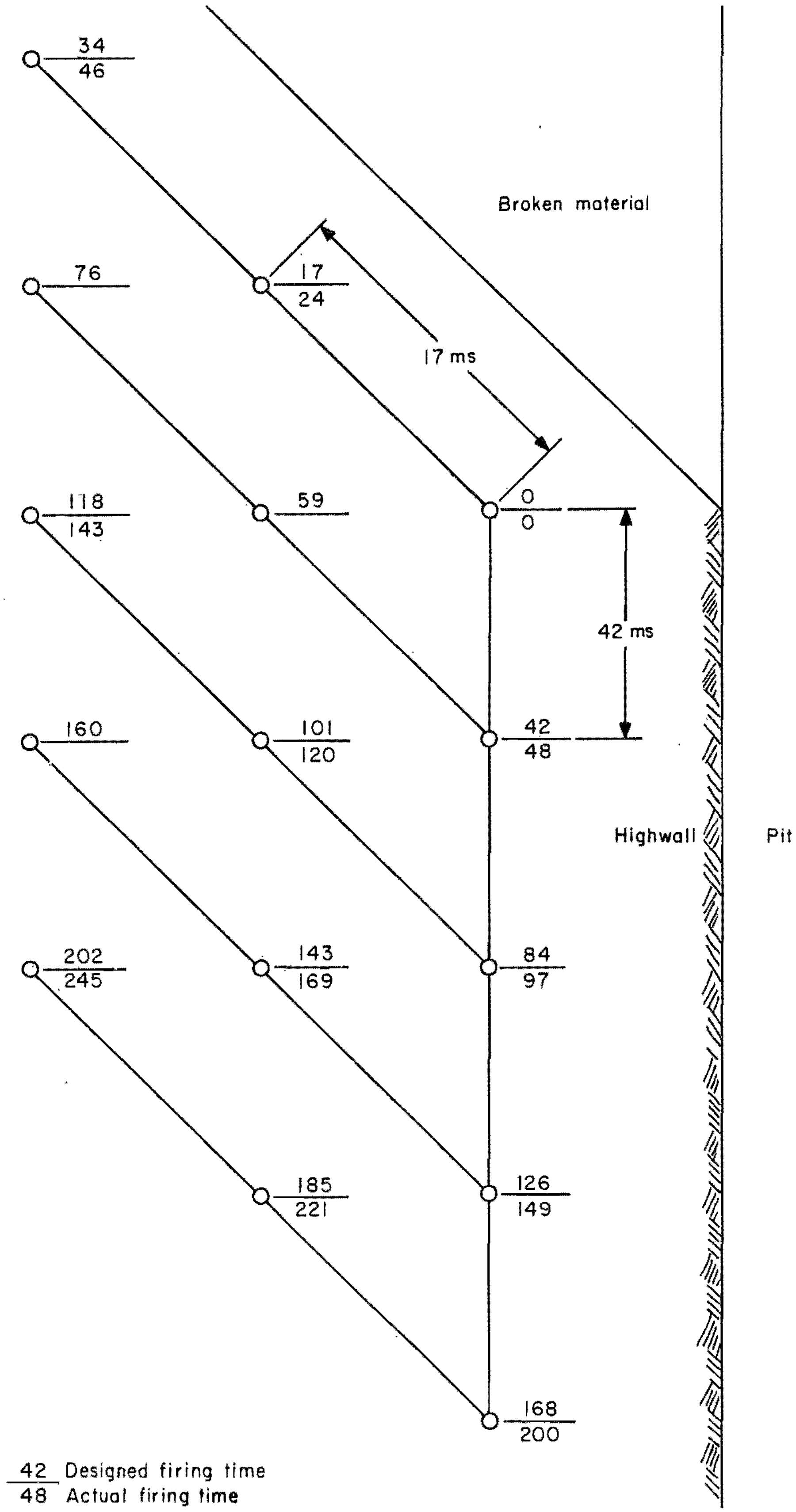

FIGURE 4. - Blast pattern for shot 32 showing planned and actual firing times.

RESULTS

PRODUCTION BLAST DATA

Data were collected from the field site during three visits in 1980, 1981, and 1982. In 1980, 13 shots were recorded, 9 of which were decked shots. In 1981, 10 shots were recorded, from which the directional effects were measured. The 1982 data involved 29 shots using 5 different delay intervals between echelons. Pertinent blast data for these shots are given in table 1. The actual firing time of each hole was verified with high speed cinematography. Delay intervals for each shot are shown in table 2.

VIBRATION DATA

Vibration and airblast data were collected on magnetic tape cassettes using self-triggered seismographs. The recordings were played back onto an oscillograph, and the peak particle velocity of each trace was calculated. The results are presented in the appendix.

Propagation plots of peak particle velocity versus the square root scaled distance were prepared for each of the blast designs used. Peak airblast was plotted against cube root scaled distance to show propagation. Data for the regression line equations are presented in table 3.

DELAY INTERVALS WITHIN ROWS

Two different delay intervals were used between adjacent holes in each echelon. These were 17-ms and 42-ms delays from shots 1 through 4. A 100-ms delay interval was used between rows. The blasts were shot at the same location in the mine using the same blast pattern.

The mine used a square pattern drilled on 25-ft centers. The pattern was fired en echelon, giving an effective burden of 18 ft and spacing of 35 ft. The actual firing times averaged 23 and 44 ms for the nominal 17- and 42-ms delays, respectively. This gave a relief of 0.7 ms/ft of spacing for the 17-ms delay shots and 1.3 ms/ft for the 42-ms delay shots. The burden delays averaged 96 ms, giving a burden relief of 5.3 ms/ft. Table 2 shows the observed delays and standard deviations from the average.

The direction of the measurement arrays from the shot did not appear to significantly affect the airblast data, as shown in figures 5 and 6 for 17- and 42-ms delays. The 17-ms design did show a trend toward the use of separate regression lines for each direction. Therefore, the data for each direction were combined and an analysis of variance performed to compare the airblast levels between the two 17- and 42-ms designs. The results are shown in figure 7. The airblast from the two designs is sufficiently different to require separate regression lines with a common slope to represent them. The design using 42-ms delays produced 6 dB less airblast than the 17-ms design.

An analysis of variance was also performed for each array direction comparing the two designs. The data were sufficiently different to require separate regression lines with a common slope for the west and north arrays but showed no difference in the east array. Comparison of propagation data is shown in figures 8-10. The south array had insufficient data for analysis. The direction of initiation of the holes in each row was toward the northwest. The airblast trace velocity for the 17-ms delay design was supersonic in the north and west direction but subsonic in the east direction. The airblast trace velocity was subsonic for the 42-ms design. The airblast from the 17-ms design was 7 dB higher in the north array and 6 dB higher in the west array, but no different in the other directions. This would indicate that the reduction in airblast is attributable to the trace velocity along the free face being subsonic for the longer delay interval.

The two blast designs also show some difference in the predominate frequencies of the airblast. The design using 17-ms delays has more airblast energy in the 10-Hz range than the 42-ms delay design, as shown in figure 11.

TABLE 1. - Data for production shots

Shot	Date	Time	Drill pattern size, ft	Burden, ft	Spacing, ft	Holes	Echelons	Explosive, lb Per delay	Explosive, lb Total
1	9/18/80	1125	25	18	35	24	4	500	11,700
2	9/18/80	1210	25	18	35	24	4	500	10,100
3	9/19/80	1110	25	18	35	24	4	500	6,800
4	9/19/80	1202	25	18	35	45	9	300	13,500
5	9/20/80	911	38	27	54	7	4	1,200	18,000
6	9/20/80	927	38	27	54	10	4	1,400	24,700
7	9/20/80	957	38	27	54	13	4	1,200	30,400
8	9/20/80	1023	38	27	54	19	5	1,200	49,200
9	9/20/80	1036	38	27	54	6	2	1,200	15,600
10	9/23/80	1000	38	27	54	9	4	1,200	20,550
11	9/23/80	1000	38	27	54	12	4	1,200	35,600
12	9/23/80	1045	38	27	54	12	4	1,200	36,500
13	9/23/80	1103	38	27	54	12	4	1,900	36,900
14	9/23/81	936	30	21	42	19	5	1,000	13,700
15	9/23/81	959	30	21	42	20	5	1,000	16,400
16	9/23/81	1034	30	21	42	28	7	1,000	23,200
17	9/23/81	1108	30	21	42	28	7	1,000	23,100
18	9/23/81	1136	30	21	42	28	7	1,000	22,500
19	9/25/81	951	30	21	42	24	6	900	19,200
20	9/25/81	1030	30	21	42	28	7	900	22,400
21	9/25/81	1059	30	21	42	28	7	900	22,400
22	9/25/81	1122	30	21	42	32	8	900	25,600
23	9/25/81	1142	30	21	42	32	8	900	25,000
24	8/20/82	857	32	23	45	12	4	2,350	25,350
25	8/20/82	918	32	23	45	12	4	2,300	26,050
26	8/20/82	938	32	23	45	9	3	2,300	18,800
27	8/20/82	959	32	23	45	19	5	2,750	33,750
28	8/20/82	1020	32	23	45	14	4	2,200	26,200
29	8/20/82	1037	32	23	45	14	4	2,250	27,700
30	8/20/82	1053	32	23	45	14	4	2,300	28,500
31	8/21/82	923	33	23	47	15	5	2,050	26,850
32	8/21/82	938	33	23	47	15	5	2,100	26,200
33	8/21/82	954	33	23	47	15	5	2,100	25,050
34	8/21/82	1007	33	23	47	15	5	2,100	26,400
35	8/21/82	1019	33	23	47	15	5	2,100	26,550
36	8/21/82	1032	33	23	47	14	4	2,150	24,950
37	8/24/82	929	33	23	47	11	3	2,200	16,300
38	8/24/82	945	33	23	47	12	3	2,150	18,650
39	8/24/82	1001	33	23	47	12	3	2,100	19,200
40	8/24/82	1013	33	23	47	12	3	2,100	19,200
41	8/24/82	1024	33	23	47	12	3	2,000	18,450
42	8/25/82	1016	33	23	47	12	3	1,800	17,450
43	8/25/82	1029	33	23	47	11	3	1,700	15,500
44	8/25/82	1043	33	23	47	12	3	1,750	16,850
45	8/26/82	947	33	23	47	12	3	1,650	16,650
46	8/26/82	1006	33	23	47	12	3	1,650	16,300
47	8/26/82	1020	33	23	47	12	3	1,650	15,950
48	8/26/82	1035	33	23	47	12	3	1,400	13,950
49	8/26/82	1048	33	23	47	12	3	1,300	12,950
50	8/27/82	1152	32	23	45	12	4	1,950	21,100
51	8/27/82	1210	32	23	45	12	4	1,850	20,450
52	8/27/82	1228	32	23	45	12	4	1,850	20,150

TABLE 2. - Observed delay intervals of production blasts, milliseconds

Shot	Spacing			Between rows		
	Nominal delay[1]	Observed delay	Standard deviation[1]	Nominal delay	Observed delay	Standard deviation[1]
1	17	23.0	2.28	100	97.8	8.66
2	17	22.2	.77	100	100.7	5.97
3	42	44.2	3.00	100	NA	NA
4	42	44.7	2.65	100	90.1	2.34
10	17	24.2	2.98	100	100.3	.42
11	17	22.6	1.33	100	101.4	2.45
12	17	21.6	.68	100	97.0	2.94
13	17	22.1	1.12	100	97.6	1.20
14	17	23.4	2.30	42	50.0	.71
15	17	NA	NA	42	NA	NA
16	17	23.7	1.25	42	48.2	2.85
17	17	23.5	5.07	42	51.0	6.08
18	17	22.1	5.37	42	50.6	4.22
19	17	23.6	1.69	42	48.2	.96
20	17	22.4	1.80	42	49.2	1.34
21	17	22.2	1.57	42	49.0	.82
22	17	21.6	.72	42	49.7	1.58
23	17	21.8	1.58	42	48.7	.88
24	17	NA	NA	42	NA	NA
25	17	NA	NA	42	NA	NA
26	17	NA	NA	42	NA	NA
27	17	23.8	.67	42	47.5	2.29
28	17	24.0	1.60	42	49.0	1.41
29	17	22.8	.41	42	45.5	.71
30	17	NA	NA	42	NA	NA
31	17	22.0	1.0	42	47.0	.71
32	17	23.0	2.14	42	50.0	1.58
33	17	NA	NA	42	NA	NA
34	17	22.0	1.22	42	49.9	.83
35	17	22.0	1.22	42	48.0	.71
36	17	23.2	.75	42	49.7	1.70
37	17	22.5	1.30	60	59.7	.5
38	17	23.0	2.00	60	58.0	0
39	17	NA	NA	60	NA	NA
40	17	NA	NA	60	NA	NA
41	17	24.2	1.47	60	58.0	1.0
42	17	22.5	1.52	30	26.0	6.0
43	17	24.0	1.22	30	29.0	2.0
44	17	24.5	1.22	30	27.5	4.5
45	17	23.6	1.41	75	77.0	2.0
46	17	23.8	.97	75	79.5	3.5
47	17	23.8	1.13	75	73.5	.5
48	17	23.5	1.07	75	75.5	2.5
49	17	23.2	1.17	75	74.5	1.5
50	17	NA	NA	100	NA	NA
51	17	23.8	3.56	100	100.0	7.48
52	17	22.8	.84	100	99.0	2.94

NA Not available. [1]From firing time.

TABLE 3. - Regression lines for data shown in the propagation figures

Shot and direction of array	Ground vibration				Airblast			
	Slope	Intercept	Std error, pct	Correl. coeff.[1]	Slope	Intercept	Std error, dB	Correl. coeff.[1]
1-2:								
North........	-2.13	1,599	11.7	1.00	-22.1	179	2.1	0.99
East.........	-1.64	168	27.4	.99	-28.7	190	2.1	.99
South........	-1.34	61	18.6	.99	-14.8	160	1.3	.96
West.........	-1.47	136	35.4	.99	-25.9	185	1.5	.99
3-4:								
North........	-1.74	311	48.6	.98	-21.2	169	4.8	.92
East.........	-1.85	700	57.0	.98	-26.6	182	1.5	.98
South........	-1.25	63	29.8	.96	NA	NA	NA	NA
West.........	-1.49	154	11.9	.99	-26.9	182	.9	.99
14-23:								
North........	-1.62	236	43.9	.97	-20.0	164	1.9	.97
East.........	-1.59	164	34.0	.92	-8.4	134	2.9	.49
South........	-1.71	177	19.9	.99	-14.8	156	1.9	.91
West.........	-1.29	87	42.3	.93	-22.1	167	5.4	.78
24-30:								
North........	-1.25	54	38.3	.90	-15.0	152	2.5	.79
East.........	-2.25	2,612	21.0	.94	-28.8	185	2.4	.76
South........	-2.09	684	34.5	.96	-23.1	170	2.4	.89
West.........	-1.64	226	26.9	.99	-17.3	153	1.3	.99
31-36:								
North........	-1.31	50	49.4	.87	-33.0	190	3.4	.92
East.........	-1.38	38	21.2	.92	-33.2	198	2.0	.91
South........	-1.08	26	32.3	.84	-29.0	182	1.5	.96
West.........	-1.27	74	27.8	.98	-21.8	163	3.1	.95
37-41:								
North........	-1.44	102	18.0	.99	-22.0	173	4.0	.92
East.........	-1.46	50	18.4	.98	-15.9	155	3.5	.78
South........	-1.31	77	22.8	.96	-21.8	164	6.3	.61
West.........	-1.47	171	18.9	.99	-24.7	173	6.5	.84
42-44:								
North........	-1.69	214	13.7	.99	-21.2	167	1.9	.98
East.........	-1.40	61	14.0	.99	-26.8	184	1.7	.97
South........	-1.27	62	5.8	.99	-27.7	178	1.1	.99
West.........	-1.11	42	17.6	.99	-24.2	173	2.1	.98
45-49:								
North........	-1.74	212	33.9	.98	-30.4	189	4.3	.92
East.........	-1.76	176	26.1	.96	-18.4	161	3.0	.63
South........	-1.44	79	27.1	.98	-28.2	180	8.2	.74
West.........	-1.06	30	32.8	.96	-24.6	173	8.4	.76
50-52:								
North........	-1.41	51	26.9	.91	-54.7	238	4.5	.90
East.........	-.95	7	17.7	.97	-20.3	159	2.9	.84
South........	-2.28	953	33.2	.92	-17.0	159	2.2	.68
West.........	-1.03	19	23.8	.88	-20.0	160	1.6	.91

NA Not available. [1]Correlation coefficient.

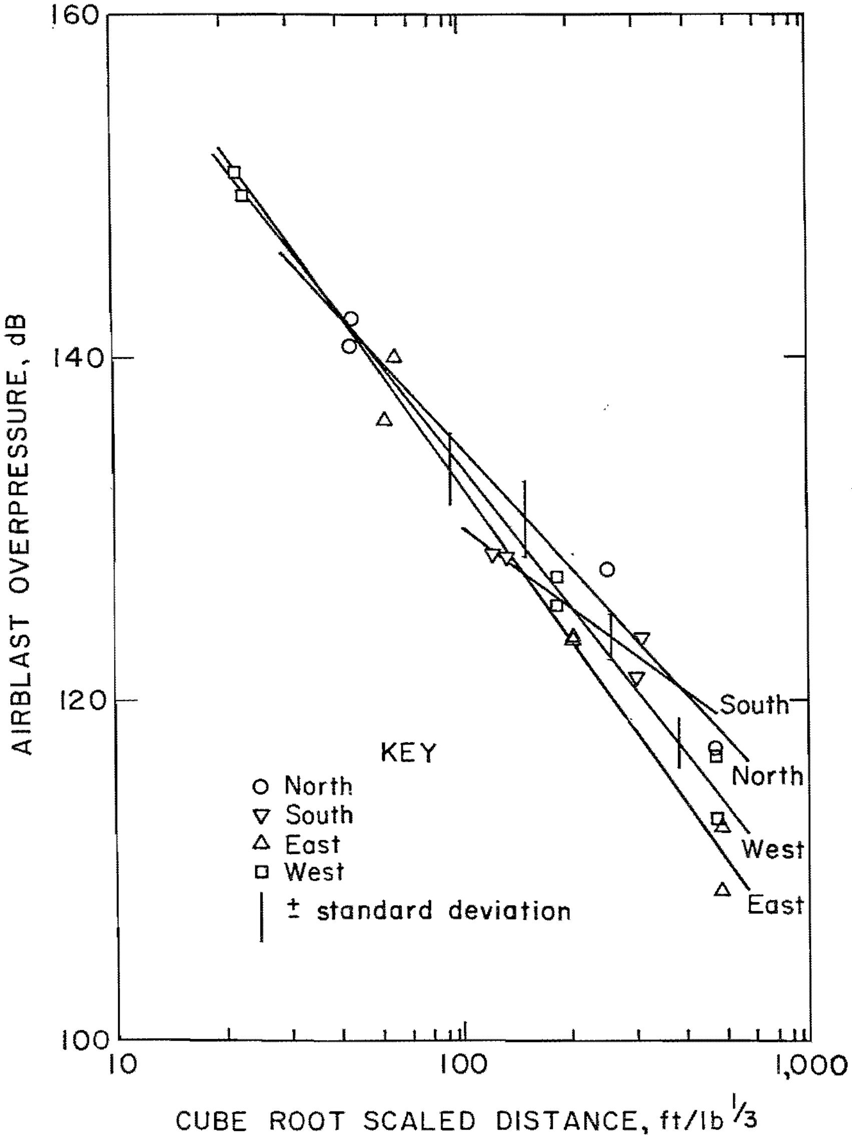

FIGURE 5. - Propagation plot of peak airblast for 18- by 35-ft burden and spacing array with 100- by 17-ms timing, shots 1-2.

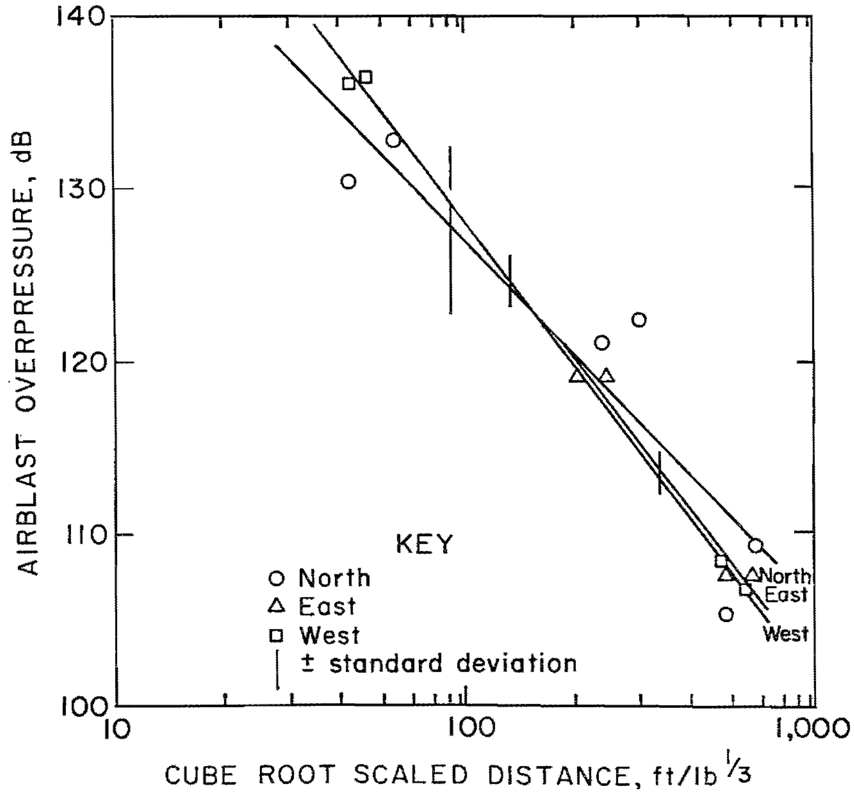

FIGURE 6. - Propagation plot of peak airblast for 18- by 35-ft burden and spacing array with 100- by 42-ms timing, shots 3-4.

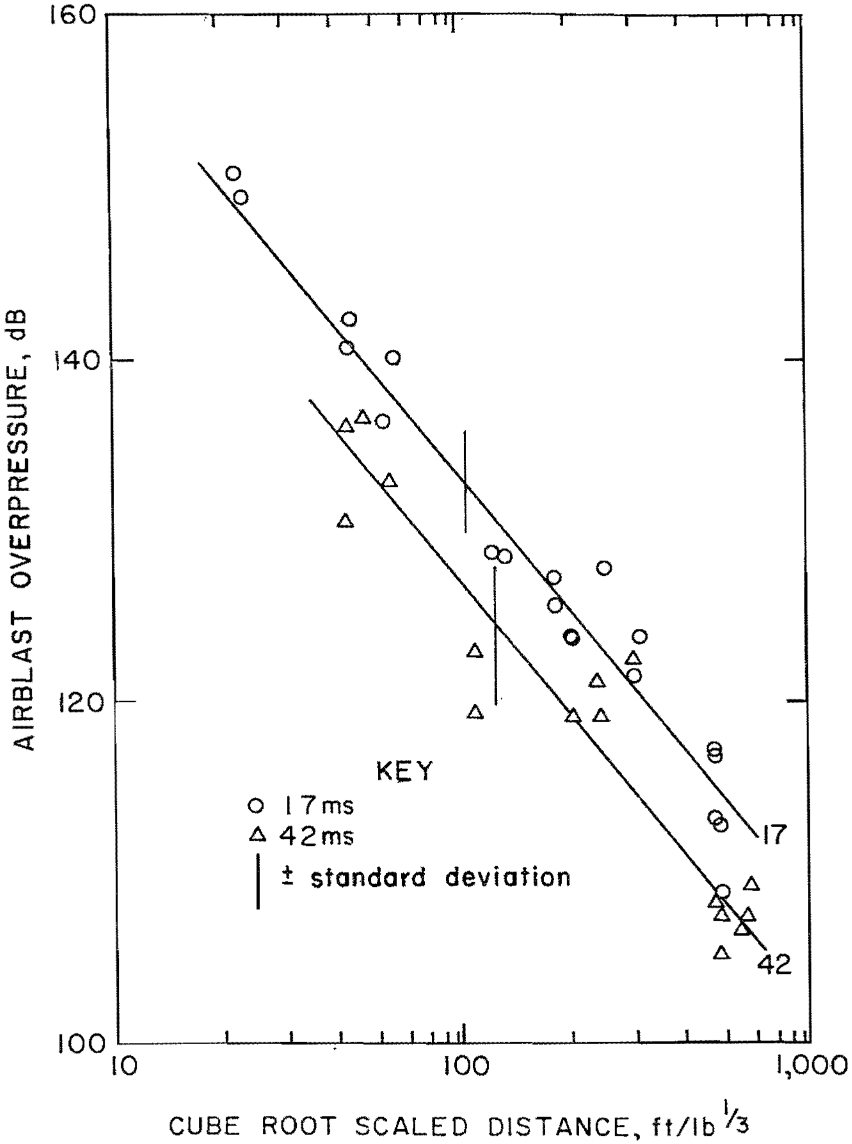

FIGURE 7. - Propagation plot showing differences in airblast level for different delay intervals between holes using all arrays.

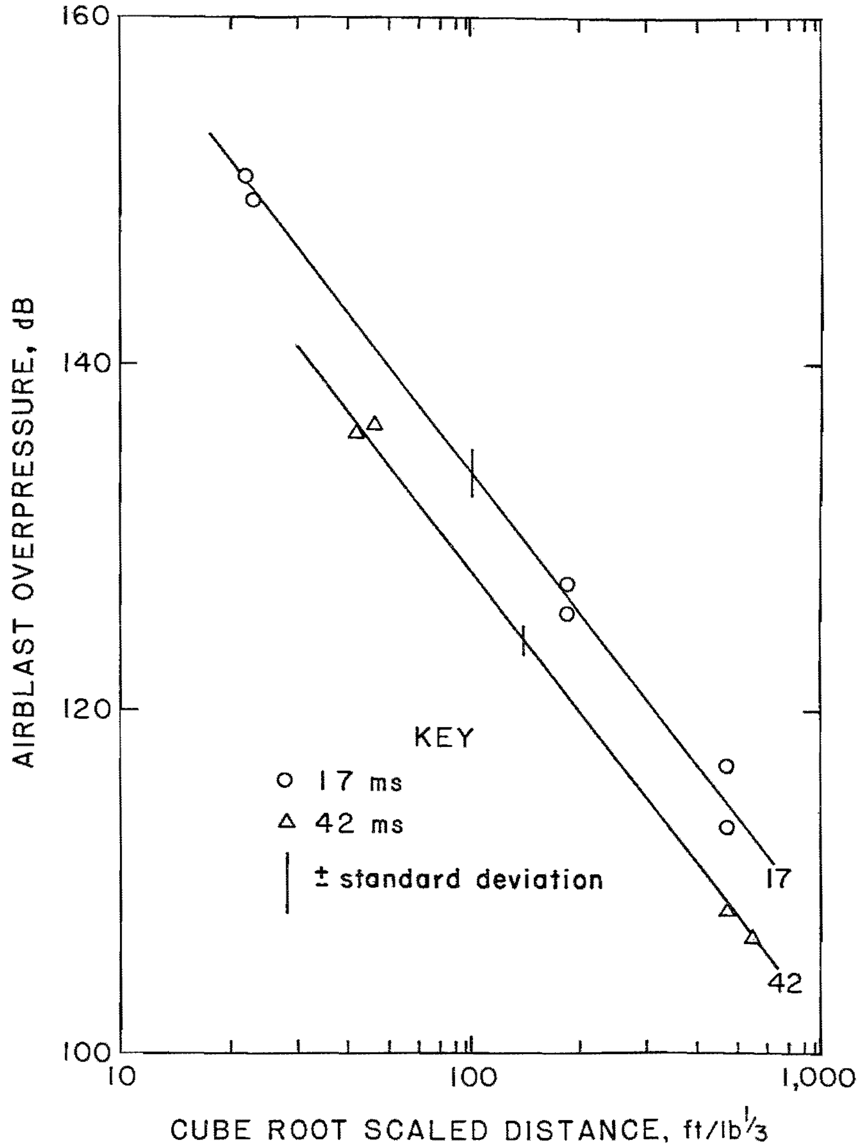

FIGURE 8. - Propagation plot showing differences in airblast levels for different delay intervals between holes for west array.

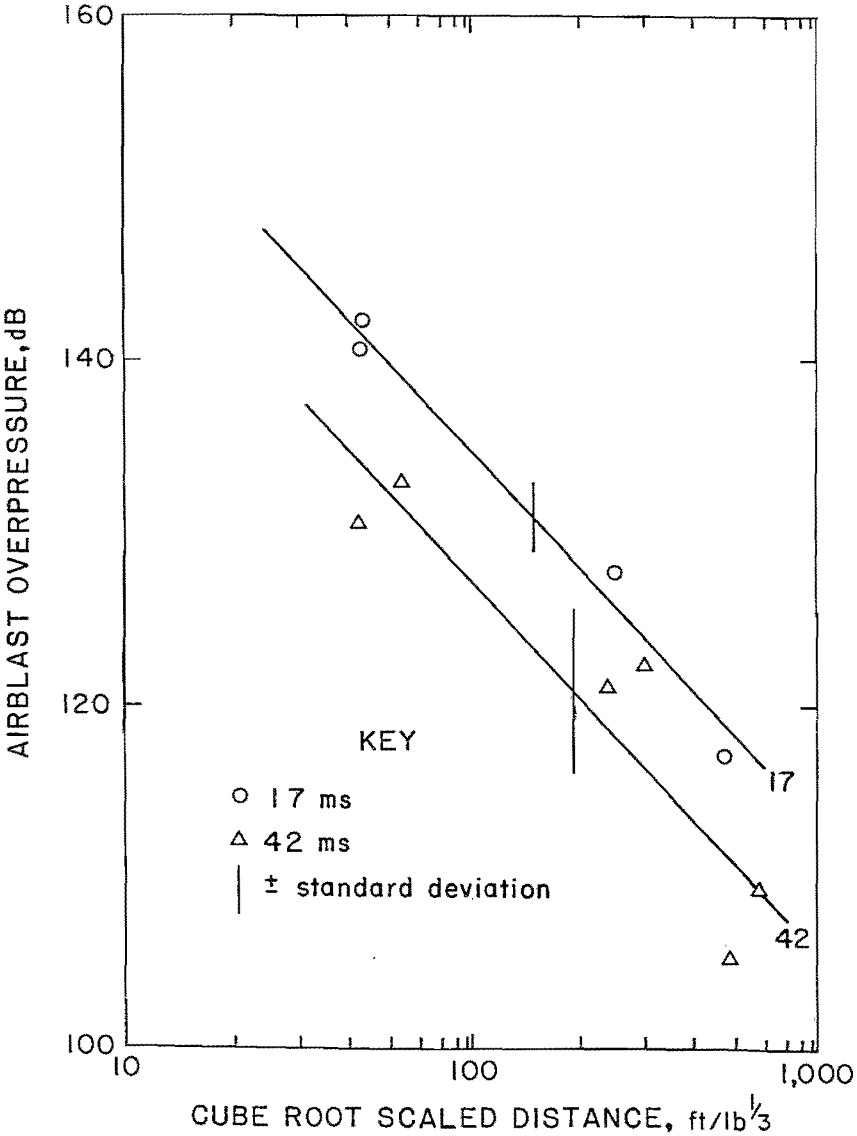

FIGURE 9. - Propagation plot showing differences in airblast levels for different delay intervals between holes for north array.

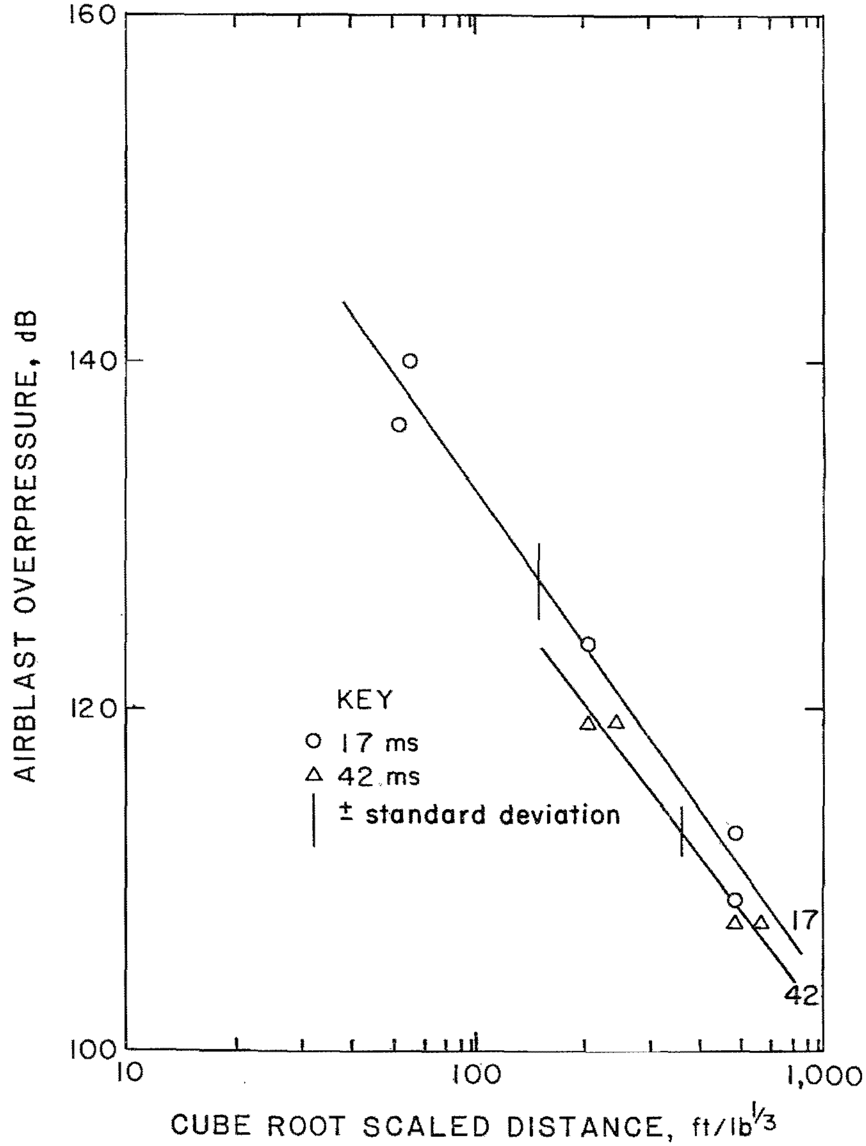

FIGURE 10. - Propagation plot showing differences in airblast levels for different delay intervals between holes for east array.

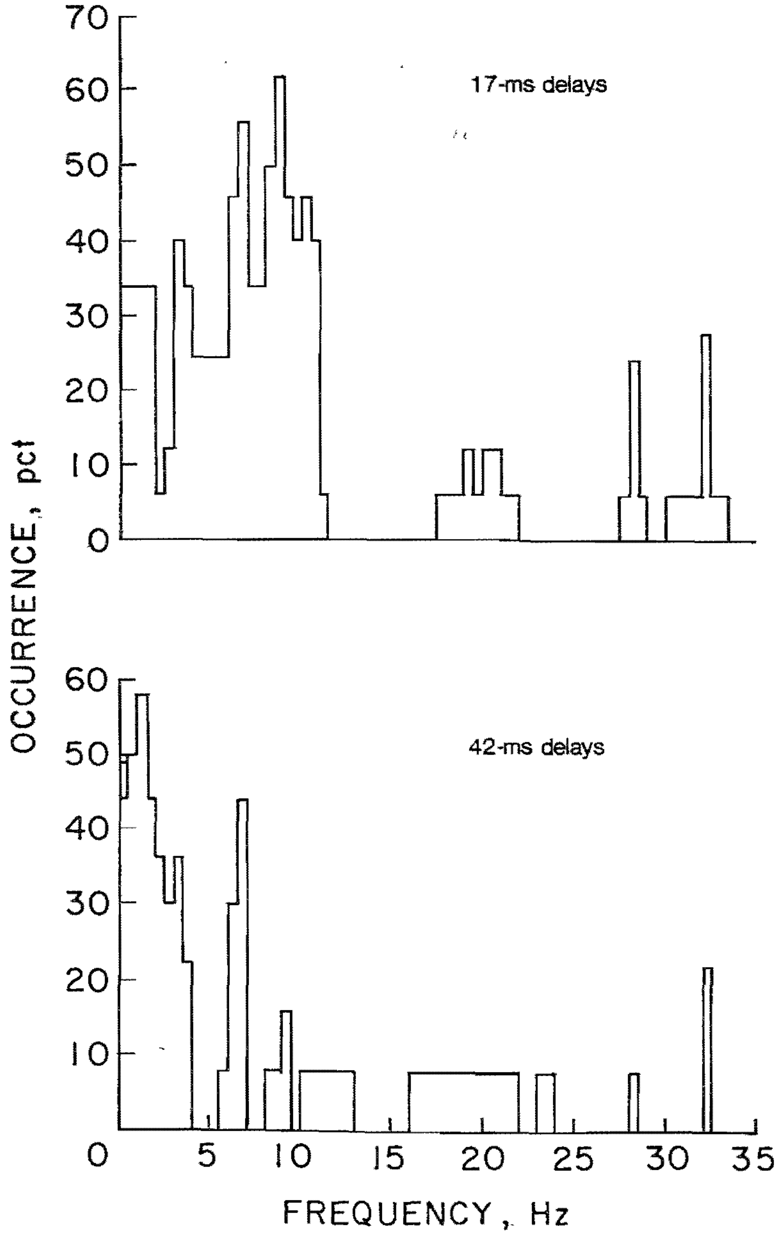

FIGURE 11. - Histogram showing spectra differences of air-blast frequency for different delay intervals between holes.

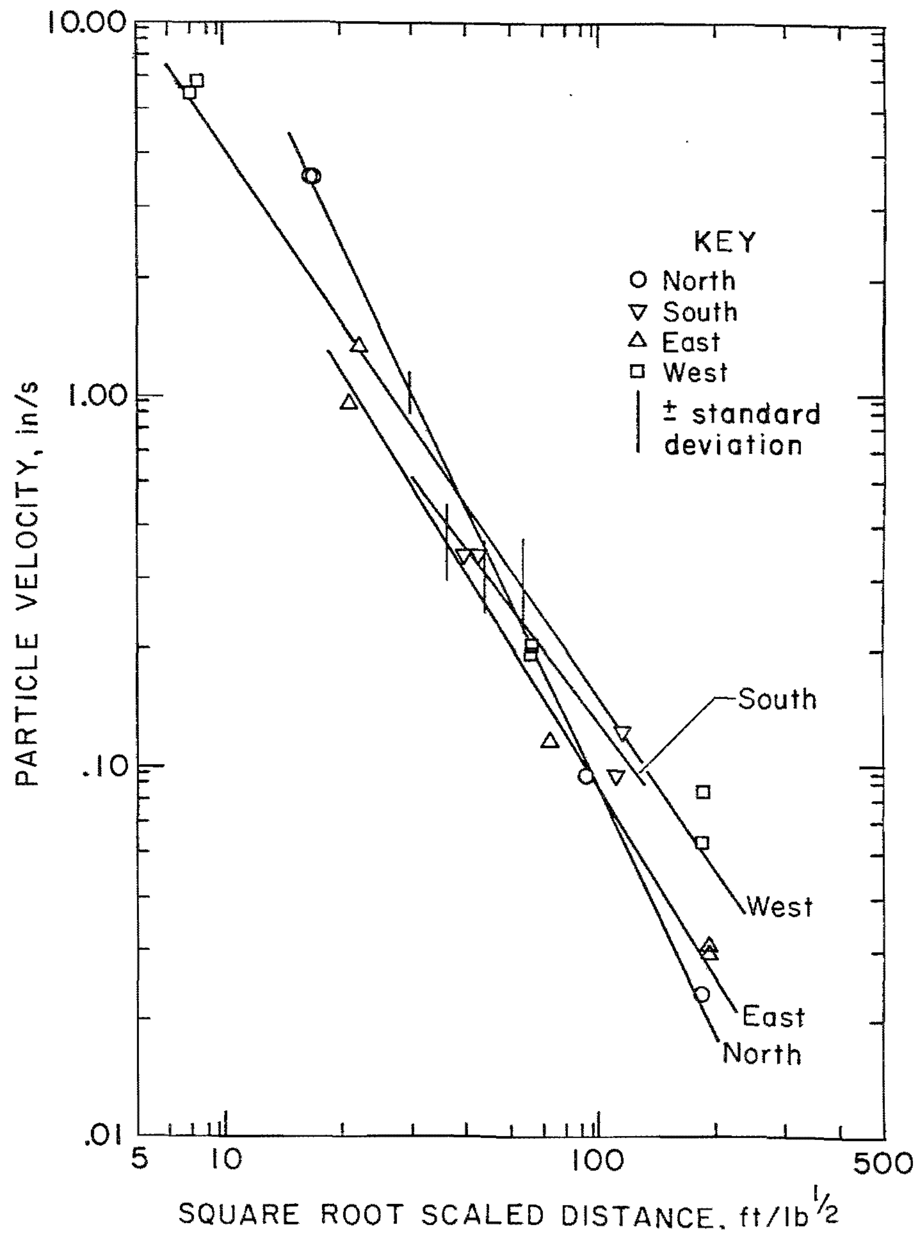

FIGURE 12. - Propagation plot of peak particle velocity for 18- by 35-ft burden and spacing array with 100- by 17-ms timing, shots 1-2.

Statistical analysis showed no significant difference in the ground vibration levels from the two blast designs. The propagation plots are shown in figures 12 and 13. However, spectral analysis did show a difference in the predominate frequencies of the two designs (fig. 14). The 17-ms design has its predominate frequencies around 10 Hz, while the 42-ms design has more scatter in its predominate frequencies.

Earlier work by the Bureau of Mines (4) has shown that residential structures have natural frequencies of 4 to 12 Hz with midwall frequencies from 11 to 25 Hz. Structures will respond more strongly to ground vibrations within these frequency ranges. It would appear from figure 14 that the 42-ms design would be preferred for the ground vibration frequencies it generated, because the strong 10-Hz frequency is avoided.

Work done with airblast effects on structures (3) showed that structures respond with midwall vibrations. Thus neither design would offer an advantage for generation of airblast based on frequency because neither design produces significant airblast in the 11- to 25-Hz range.

Delay interval between holes should be selected such that the trace velocity along the free face is subsonic. Doing this resulted in a reduction of airblast of up to 6 dB in these tests. The delay interval selected between holes did not affect ground vibration amplitudes in these tests.

DELAY INTERVALS BETWEEN ROWS

Shots 24 through 52 used the same delay between holes in a row, but the delays between the burden rows were varied. The mine was using a design of 17-ms delays between holes. The delay interval between holes was kept the same; the interval was varied in five steps between rows from 30 to 100 ms. The shot pattern was 33 ft square shot en echelon, giving an effective burden of 23 ft and effective spacing of 47 ft.

The average value of the actual delay interval between holes was 23 ms for these shots. This gives a relief of about 1 ms per foot of burden, which is just sufficient for good fragmentation as reported by Bergmann (16). Five different delay intervals were used to study the effect of burden delay timing on vibration levels. Intervals used were 42 ms, which was the delay used by the mine, and 30, 60, 75, and 100 ms. The 42 ms was a pyrotechnical delay, while the others were selected using a multicircuit sequential blasting machine. The accuracy of the delays is shown in table 2 as actual firing times and standard deviations from the firing times. Table 4 gives values of burden relief for the different burden delays used.

TABLE 4. - Effective values of burden[1] delay intervals

Shot	Delay interval, ms		Burden relief,
	Nominal	Actual	ms/ft (actual)
42-44	30	27.5	1.2
24-36	42	48.5	2.1
37-41	60	58.5	2.5
45-49	75	76.0	3.3
50-52	100	99.5	4.3

[1]Actual burden 23 ft for all shots.

Vibration data for each design were compared to determine if direction of orientation of the seismograph array was important. Propagation plots of the designs are shown in figures 15-20. Table 3 presents the statistics of the regression lines in these figures. Significant differences were found, as discussed in the section on directional effects. The eastern array (in the spoils) had the lowest vibration levels; the highest levels were toward the west, where the ground was undisturbed. The vibration levels of the other arrays were intermediate between these levels. The western and northern vibration arrays were chosen for further analysis.

Vibration levels of the different designs were compared for the north and west arrays using regression analysis and the F-test. Results indicated that the vibration levels for the different designs are significantly different at a confidence level of 99 pct. Thus, the vibration data for each blast design should be represented by a separate

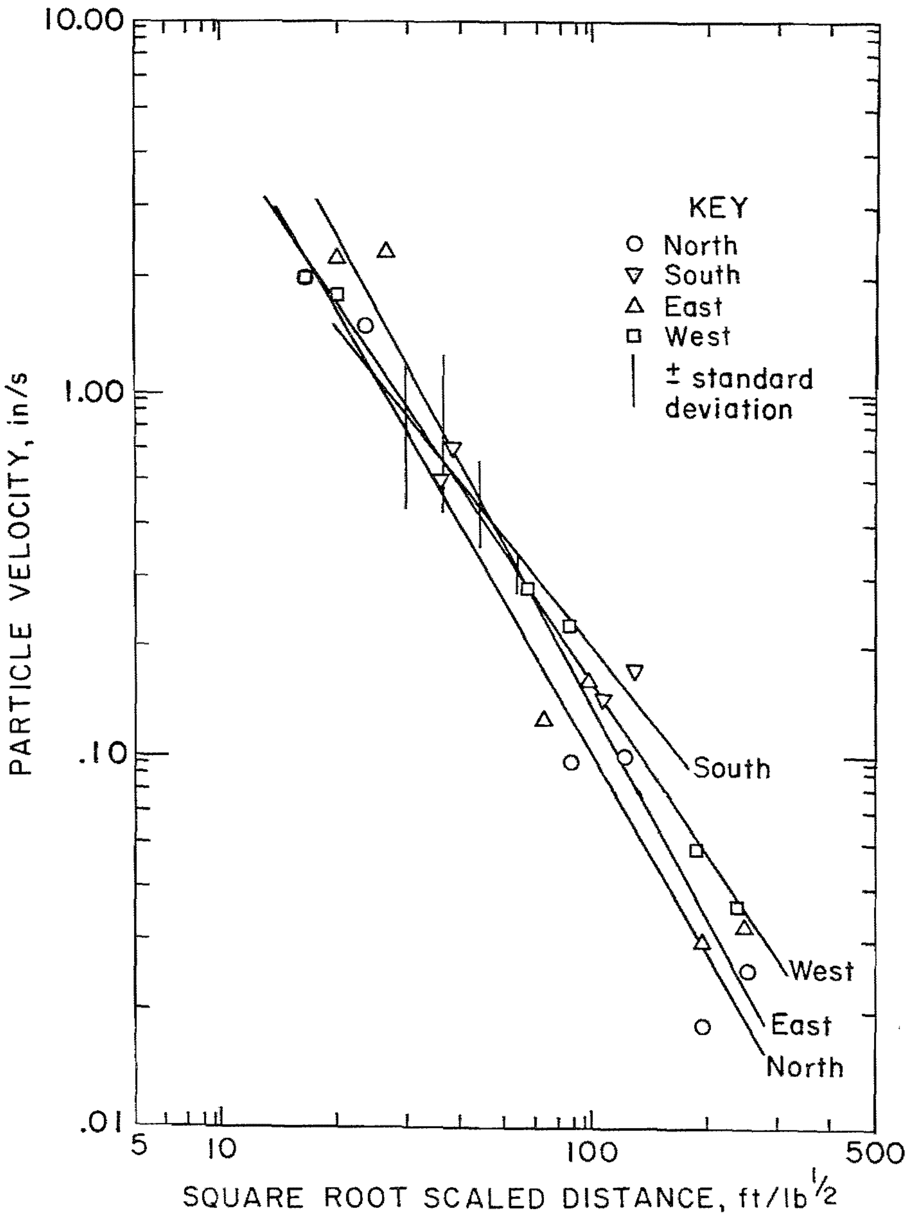

FIGURE 13. - Propagation plot of peak particle velocity for 18- by 35-ft burden and spacing array with 100- by 42-ms timing, shots 3-4.

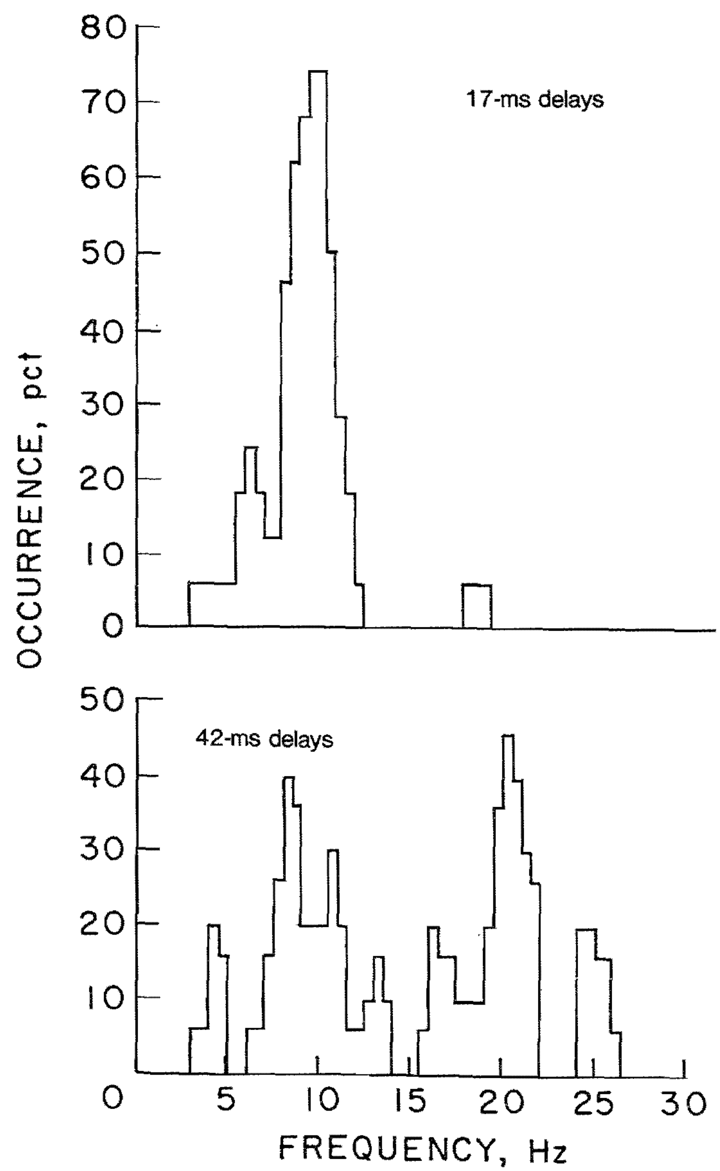

FIGURE 14. - Histogram of frequency spectra differences of ground vibrations for different delay intervals between holes.

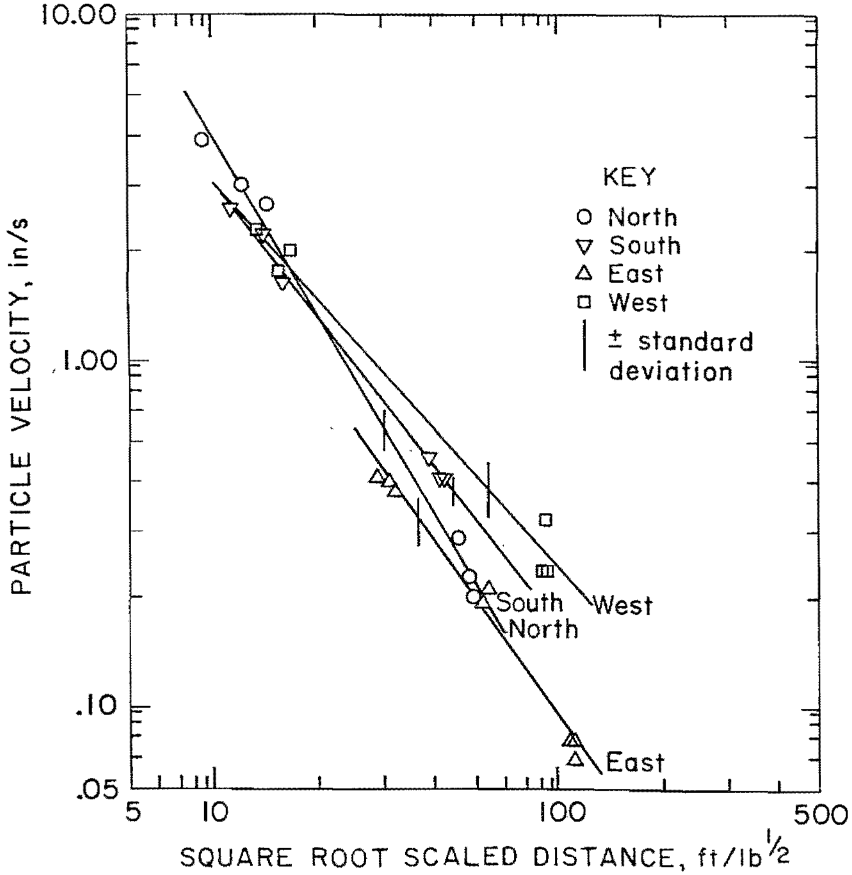

FIGURE 15. - Propagation plot of peak particle velocity for 23- by 47-ft burden and spacing array with 30- by 17-ms timing, shots 42-44.

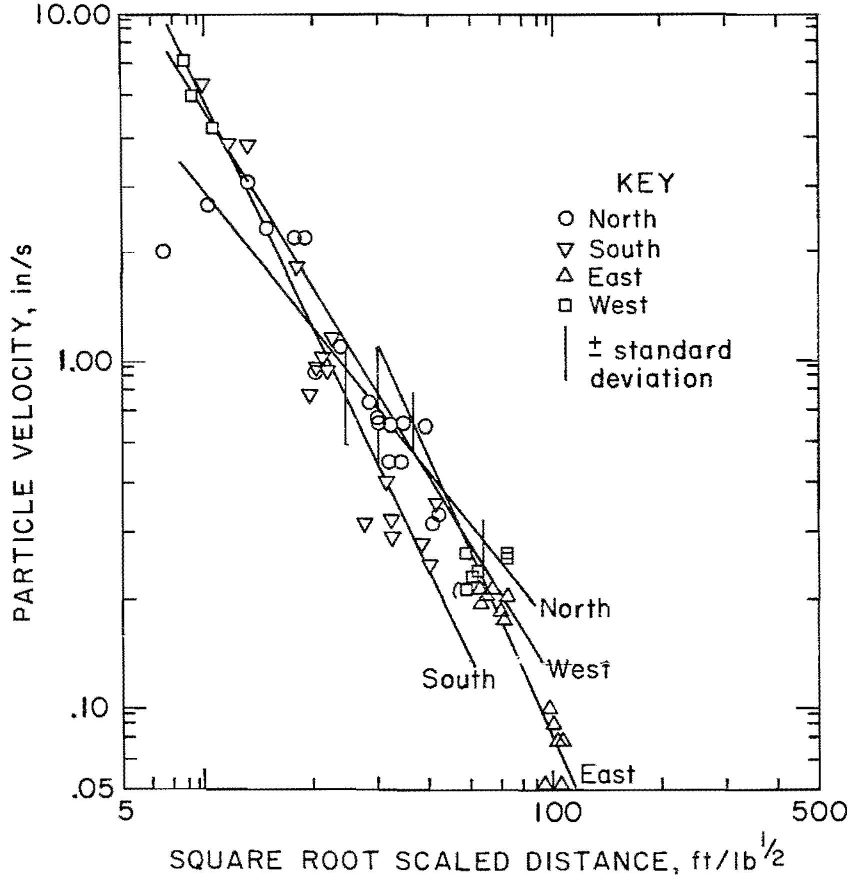

FIGURE 16. - Propagation plot of peak particle velocity for 23- by 45-ft burden and spacing array with 42- by 17-ms timing, shots 24-30.

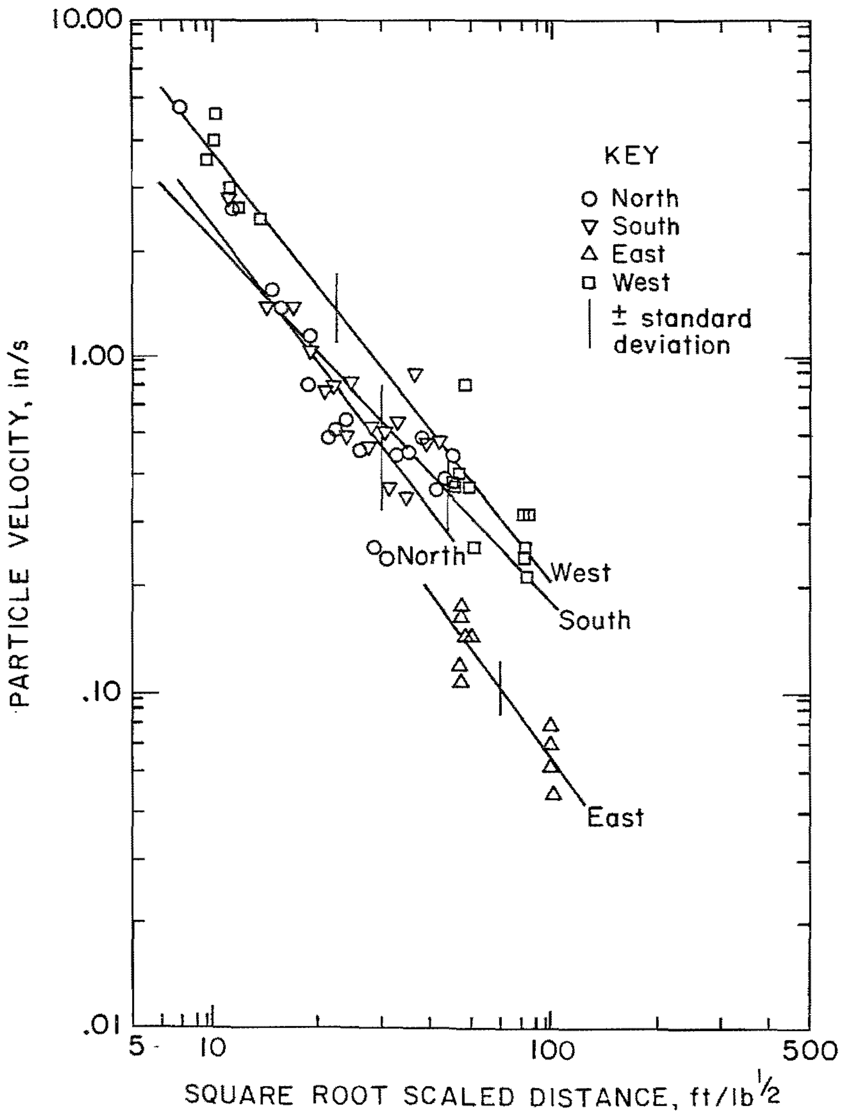

FIGURE 17. - Propagation plot of peak particle velocity for 23- by 47-ft burden and spacing array with 42- by 17-ms timing, shots 31-36.

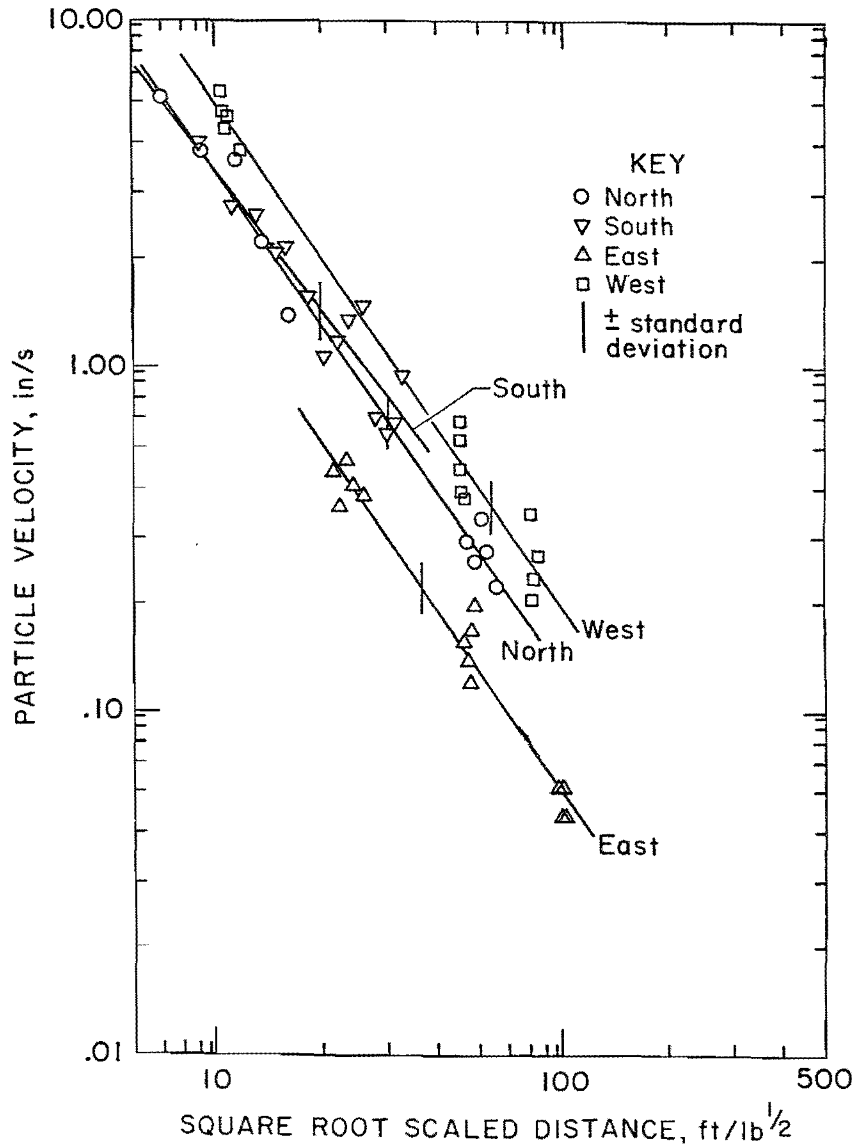

FIGURE 18. - Propagation plot of peak particle velocity for 23- by 47-ft burden and spacing array with 60- by 17-ms timing, shots 37-41.

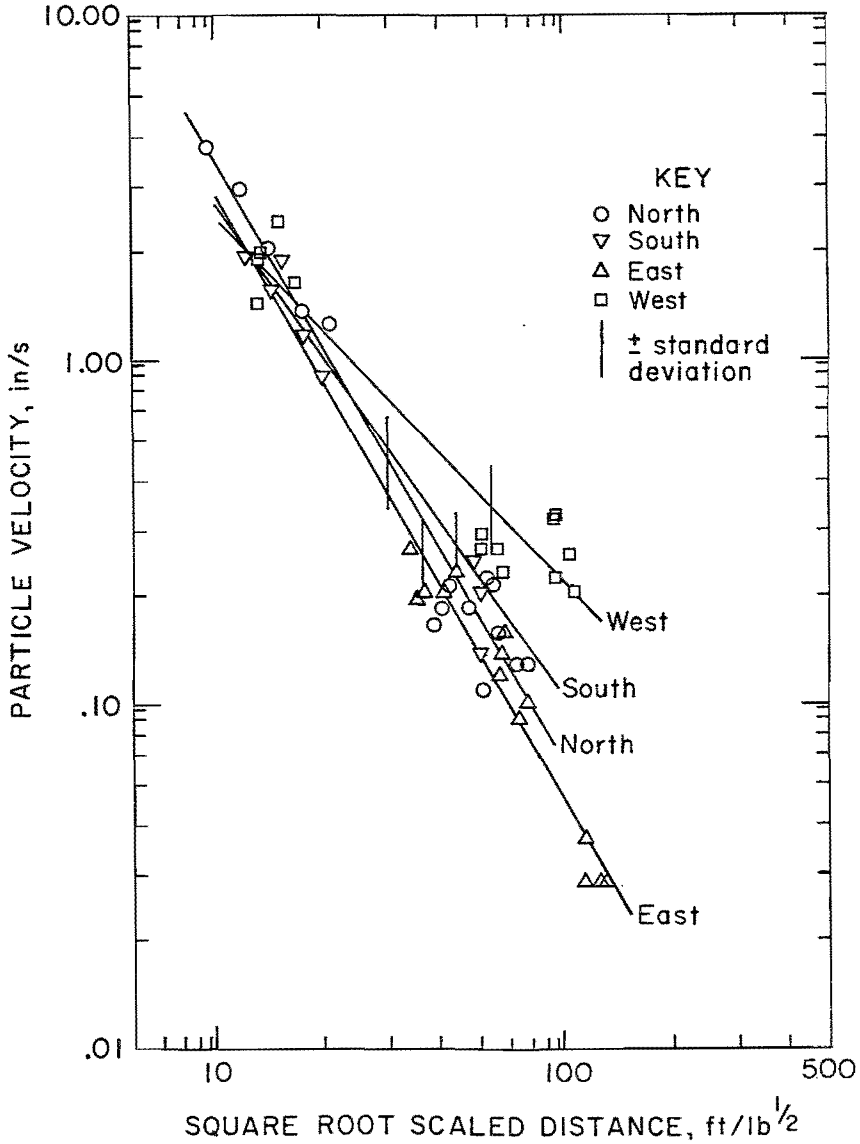

FIGURE 19. - Propagation plot of peak particle velocity for 23- by 47-ft burden and spacing array with 75- by 17-ms timing, shots 45-49.

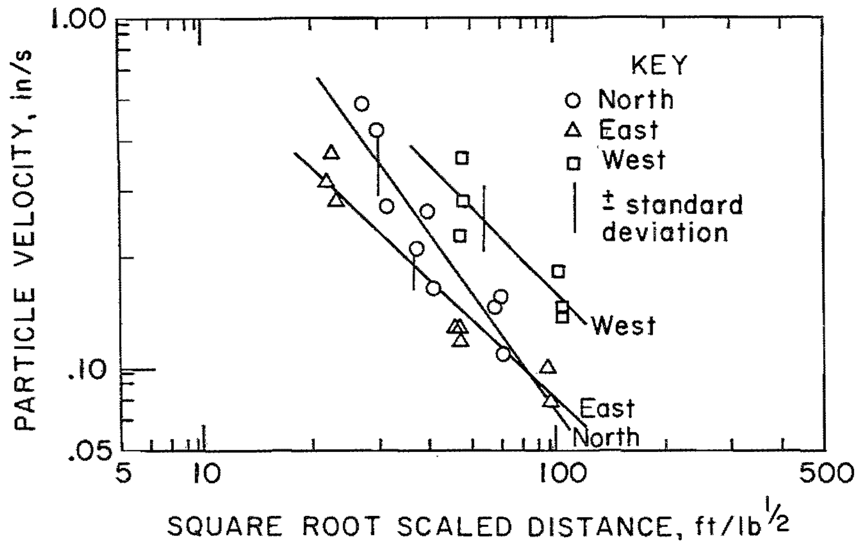

FIGURE 20. - Propagation plot of peak particle velocity for 23- by 45-ft burden and spacing array with 100- by 17-ms timing, shots 50-52.

regression line. The F-2 test showed that the regression lines have a common slope. This would indicate that the rate of decay of vibration amplitude with distance is the same for all designs, but that levels of vibrations are different. The vibration data with regression lines are presented in figures 21 and 22. Table 5 gives values of intercepts for regression lines with common slopes and shows that the longer delay intervals result in the lower vibration levels.

The three shortest delay periods are clustered at the highest vibration levels; the 60-ms delay shows the highest vibration levels. The analysis of variance test was applied to the three shortest periods, 30, 42, and 60 ms; there was no significant difference in vibration levels between them. Thus, only the two longest delay intervals affect the ground vibration levels. Looking at the burden relief values in table 4, these results suggest that vibration levels can be lowered if a certain burden relief value is exceeded, in this case about 3.0 ms/ft. This is probably due to sufficient time being allowed for the burden to move before the next echelon of holes is initiated. Similar results were reported by Andrews (13) and Winzer (17) with respect to fragmentation. This research tested a maximum burden relief of 4.3 ms/ft for the 100-ms delay, which showed the lowest vibration level. Longer delay intervals may result in further reductions in vibration levels. This series of tests showed a 30-pct reduction in vibration levels of the 100-ms design compared to the 42-ms design normally used by the mine.

Also studied was the frequency content of the ground vibrations. Spectrum analysis was performed on the vibration time histories. Results of this analysis are shown in figures 23 through 26. The delay intervals tested did not show a direct correlation with the frequency range of vibrations, which would suggest that geology was the predominate influence on the frequency of vibrations. The radial component of ground vibration for the western array (fig. 24) shows principal frequencies of 13 and 10 Hz produced by the two longest delays (75 and 100 ms); the shorter delays show no such correlation. However, the short periods produced low-frequency vibrations also, generally in the range of less than 15 Hz, which is potentially damaging to structures.

Airblast was also analyzed. No significant differences in levels of airblast were observed between the different designs. No differences were observed in the frequency spectra for the various designs. Propagation plots of the airblast data are presented in figures 27 through 32.

TABLE 5. - Comparison of regression lines for various burden delay intervals

Shot	Burden delay interval, ms	Array direction	Regression line		Regression line with common slope	
			Slope	Intercept	Slope	Intercept
42-44	30	North.............	-1.69	214	-1.50	116
24-36	42	...do.............	-1.29	53	-1.50	104
37-41	60	...do.............	-1.44	102	-1.50	122
45-49	75	...do.............	-1.74	212	-1.50	87
50-52	100	...do.............	-1.41	51	-1.50	71
42-44	30	West..............	-1.11	42	-1.25	71
24-36	42	...do.............	-1.27	77	-1.25	73
37-41	60	...do.............	-1.47	171	-1.25	80
45-49	75	...do.............	-1.06	30	-1.25	63
50-52	100	...do.............	-1.03	19	-1.25	50

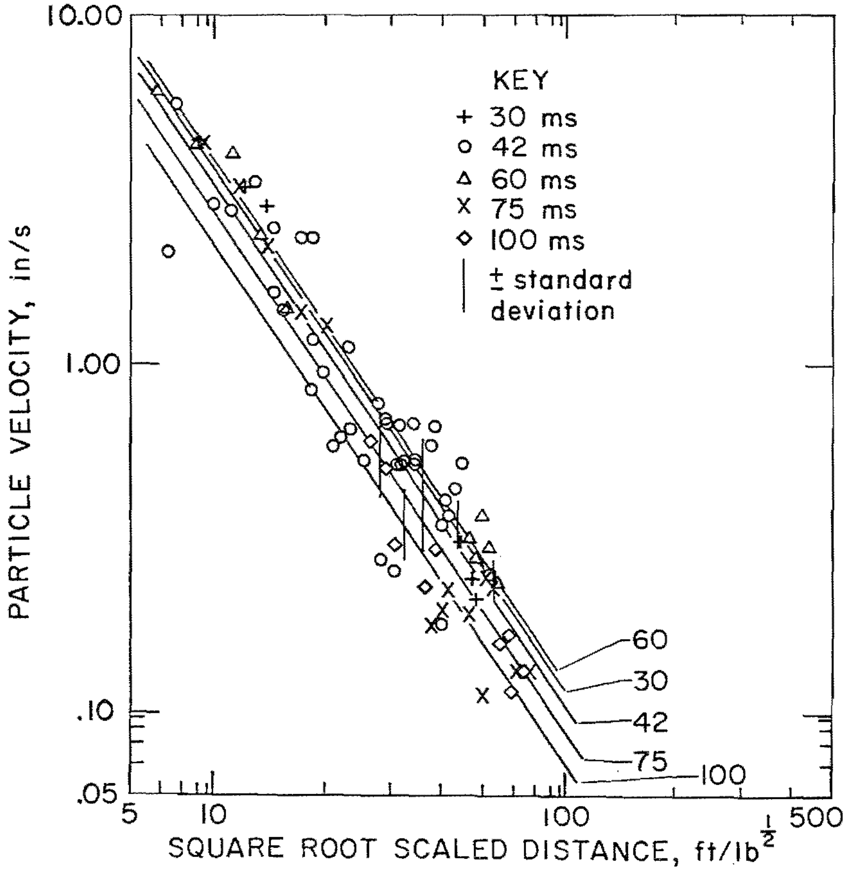

FIGURE 21. - Propagation plot of peak particle velocity for 23- by 46±1-ft burden and spacing array with five burden timings, shots 24-52: north array.

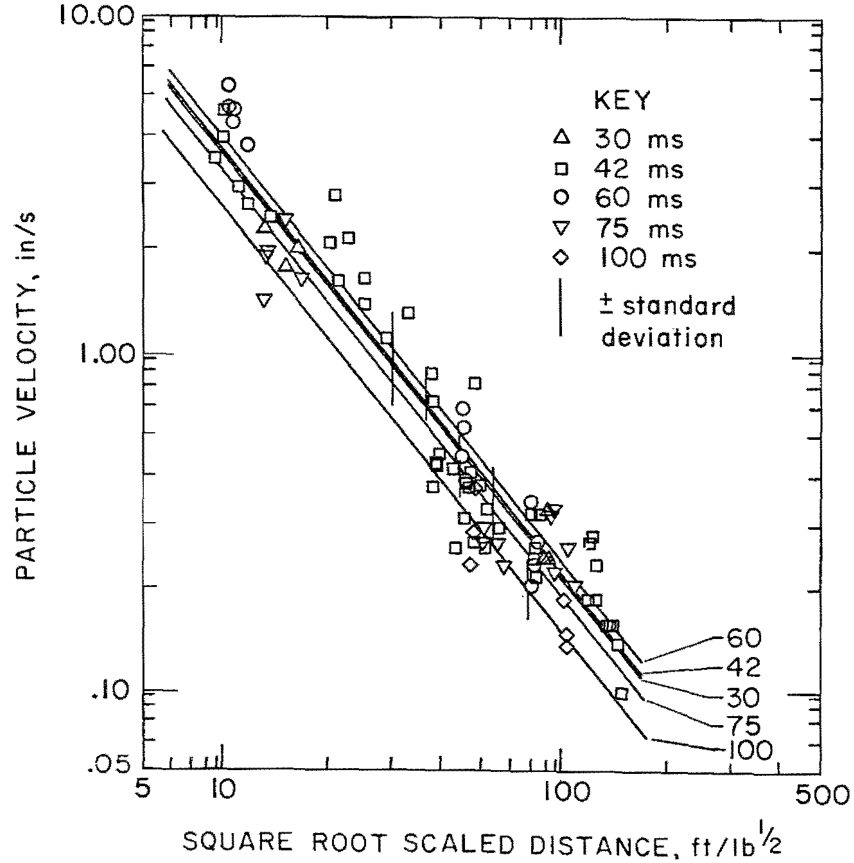

FIGURE 22. - Propagation plot of peak particle velocity for 23- by 46±1-ft burden and spacing array with five burden timings, shots 24-52: west array.

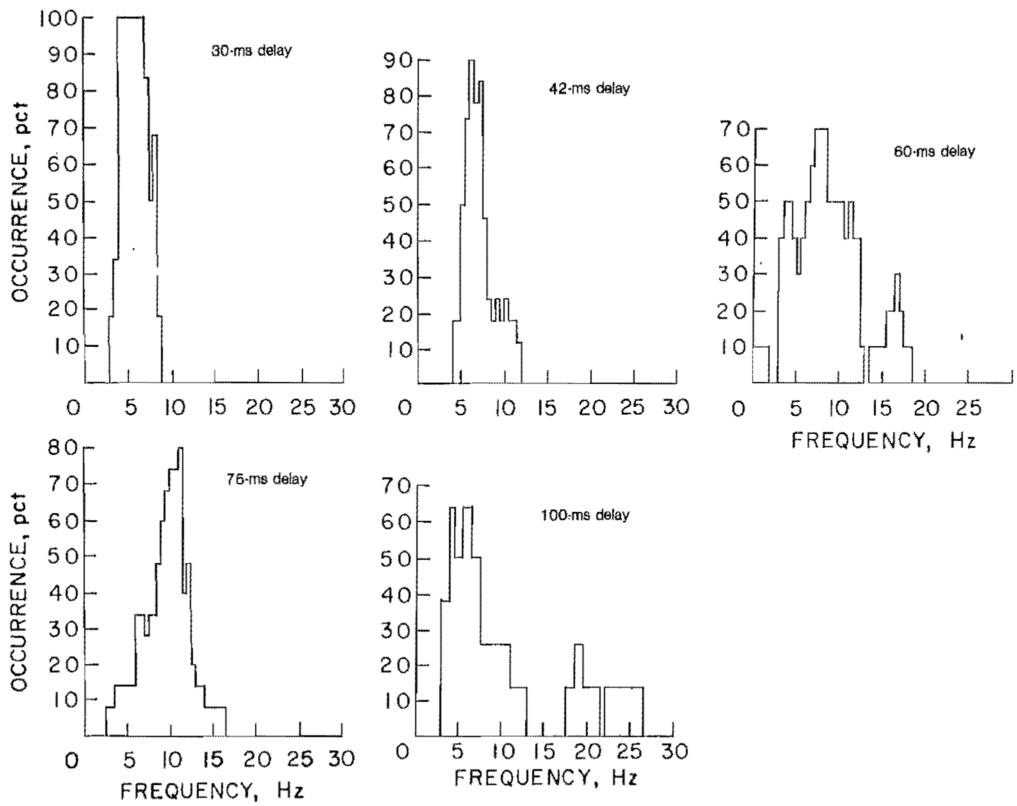

FIGURE 23. - Histogram comparing frequency differences of blast designs for radial component of vibration of north array.

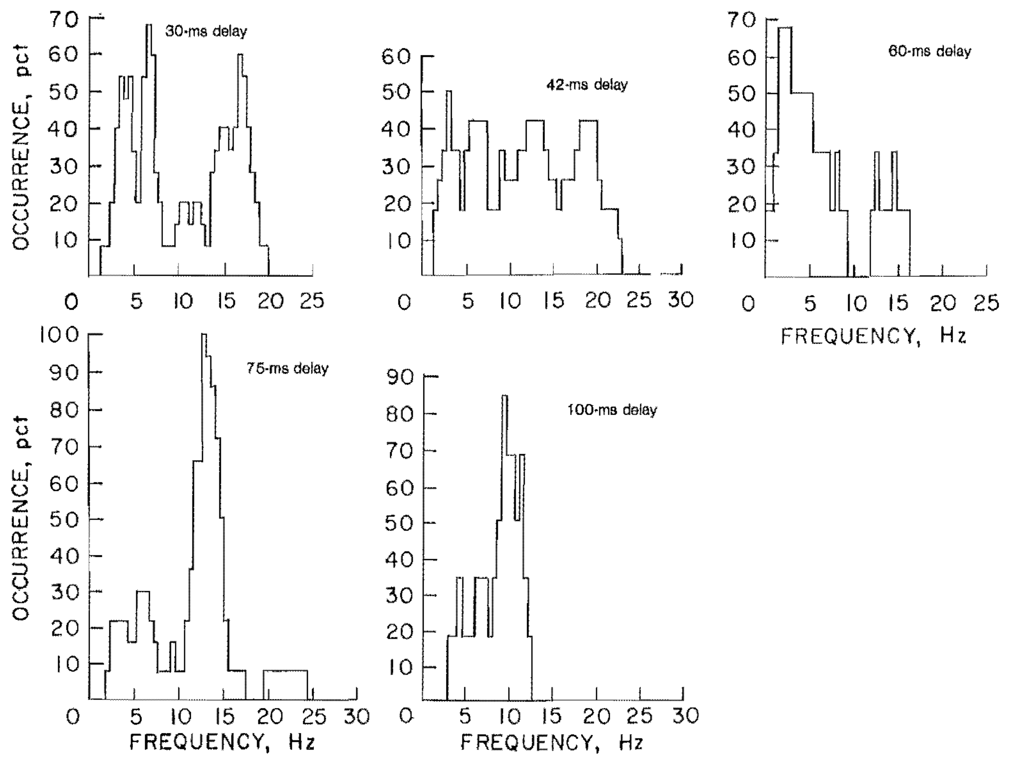

FIGURE 24. - Histogram comparing frequency differences of blast designs for radial component of vibration of west array.

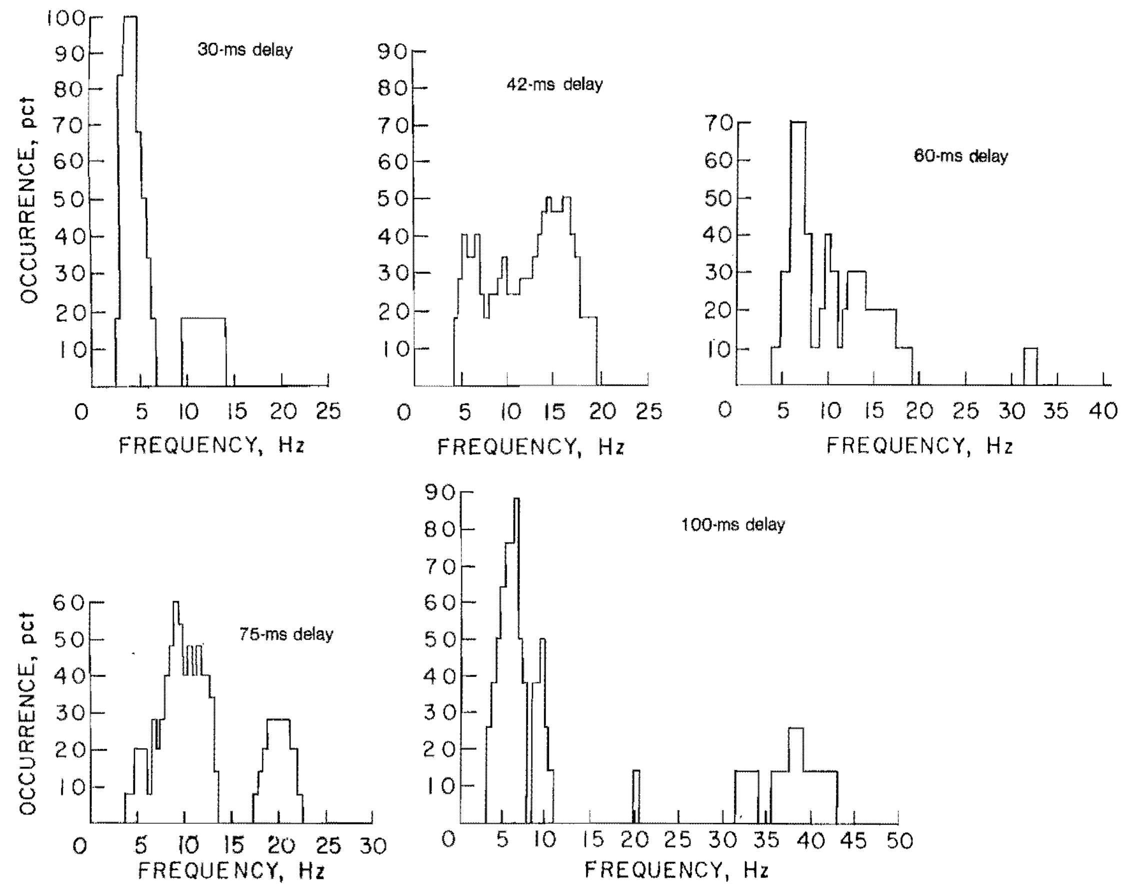

FIGURE 25. - Histogram comparing frequency differences of blast designs for vertical component of vibration of north array.

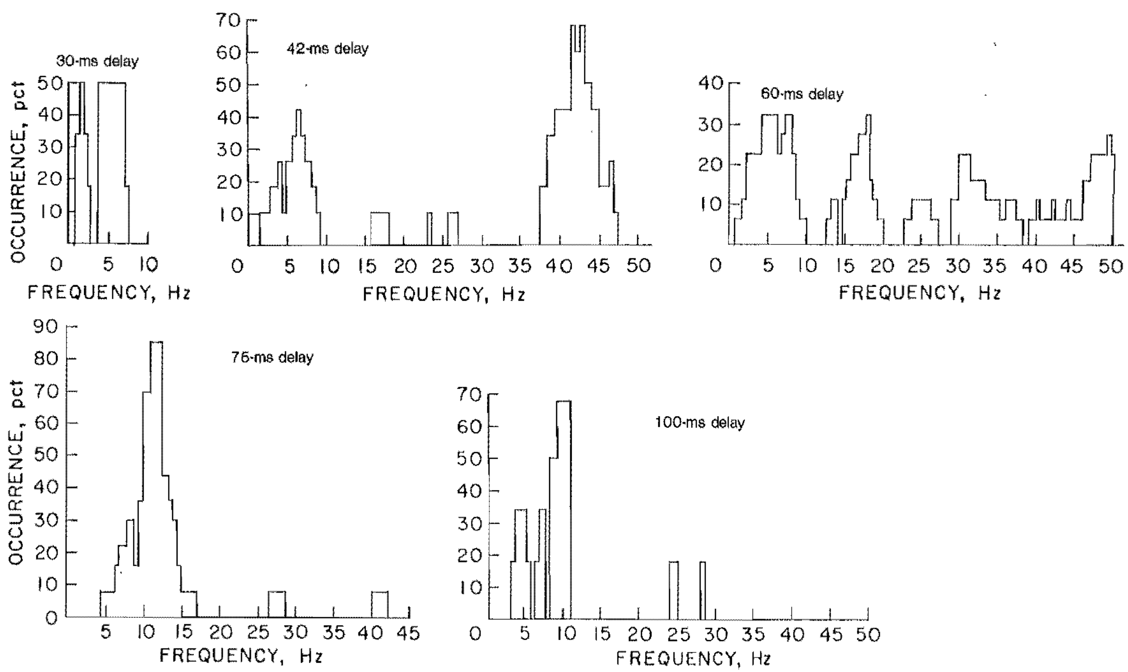

FIGURE 26. - Histogram comparing frequency differences of blast designs for vertical component of vibration of west array.

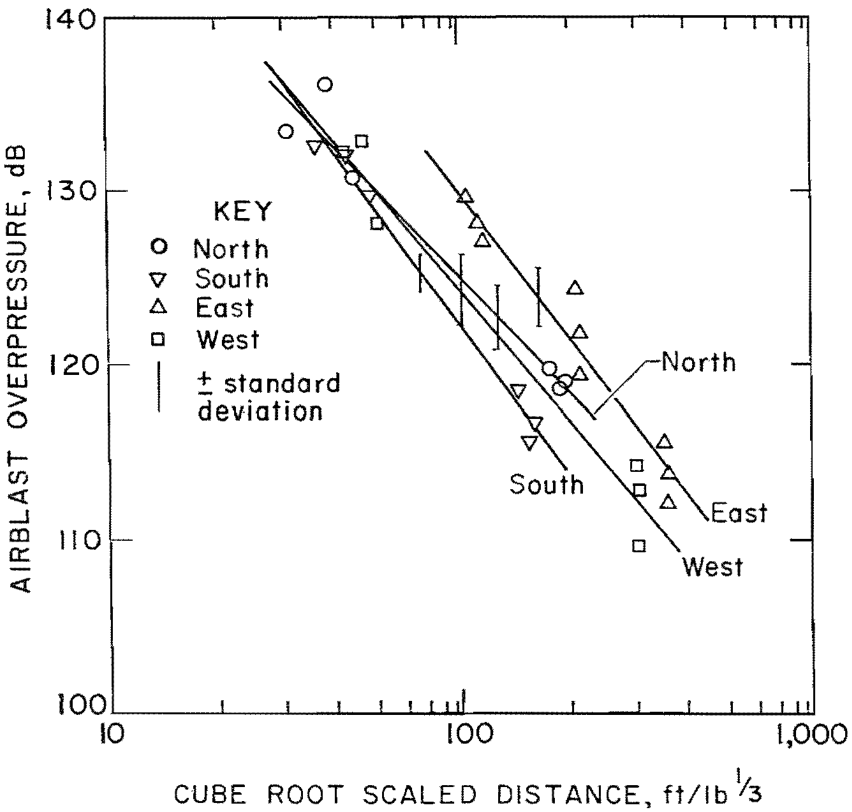

FIGURE 27. - Propagation plot of peak airblast for 23- by 47-ft burden and spacing array with 30- by 17-ms timing, shots 42-44.

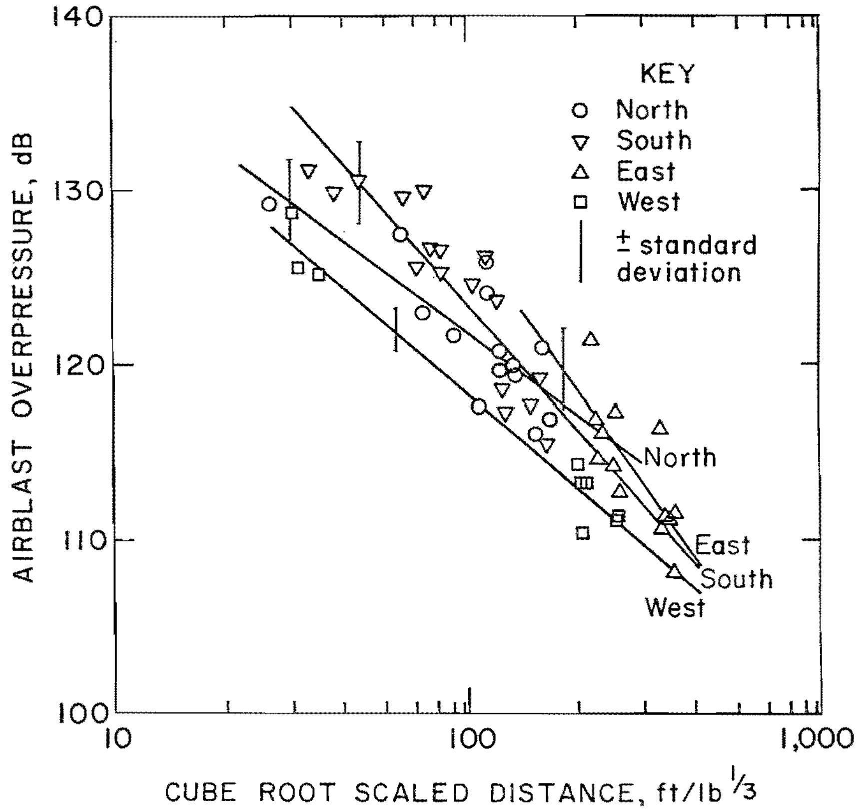

FIGURE 28. - Propagation plot of peak airblast for 23- by 45-ft burden and spacing array with 42- by 17-ms timing, shots 24-30.

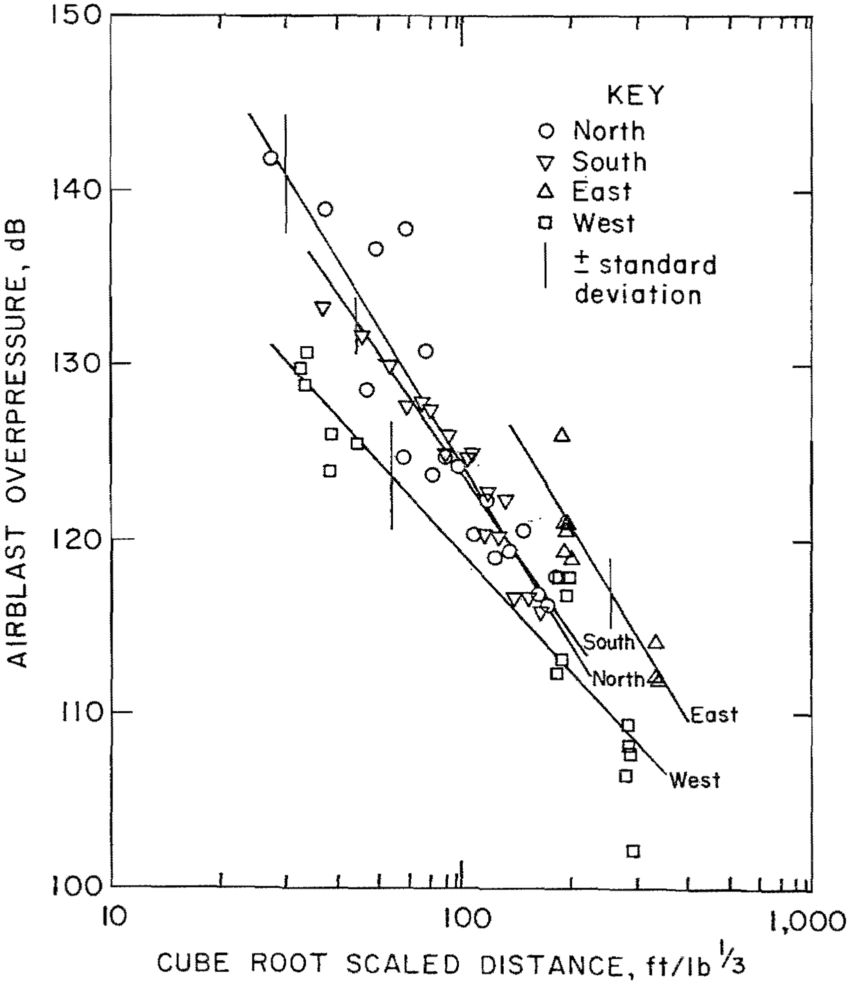

FIGURE 29. Propagation plot of peak airblast for 23- by 47-ft burden and spacing array with 42- by 17-ms timing, shots 31-36.

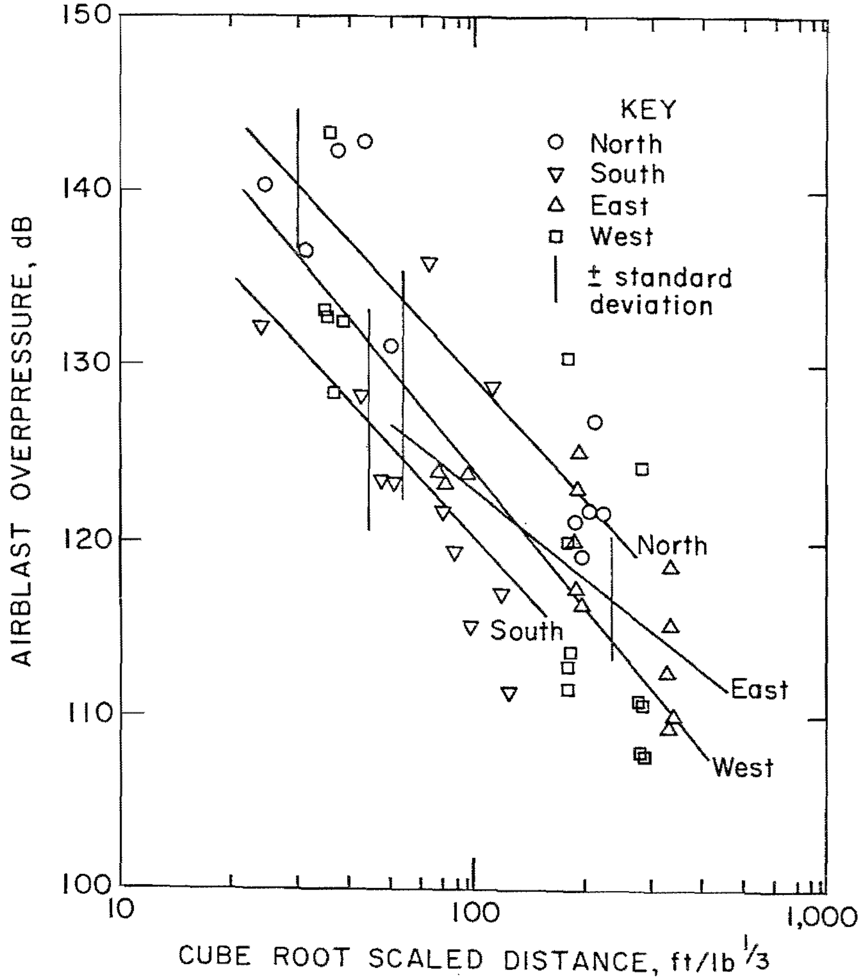

FIGURE 30. - Propagation plot of peak airblast for 23- by 47-ft burden and spacing array with 60- by 17-ms timing, shots 37-41.

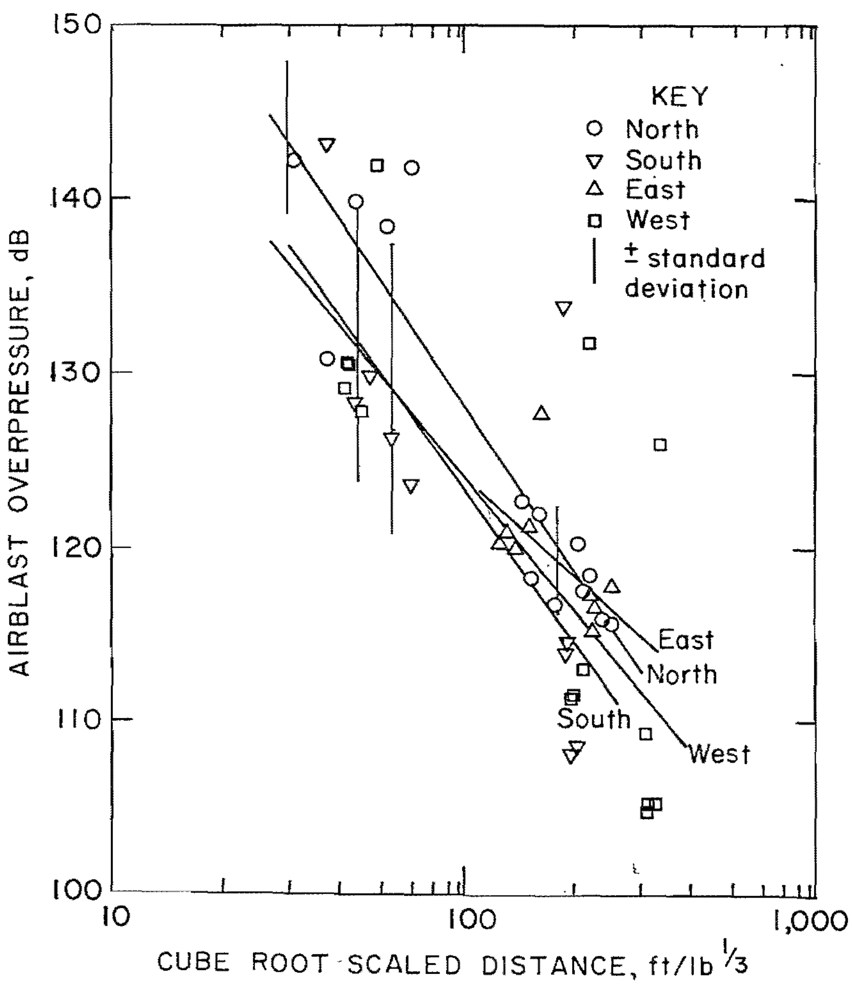

FIGURE 31. - Propagation plot of peak airblast for 23- by 47-ft burden and spacing array with 75- by 17-ms timing, shots 45-49.

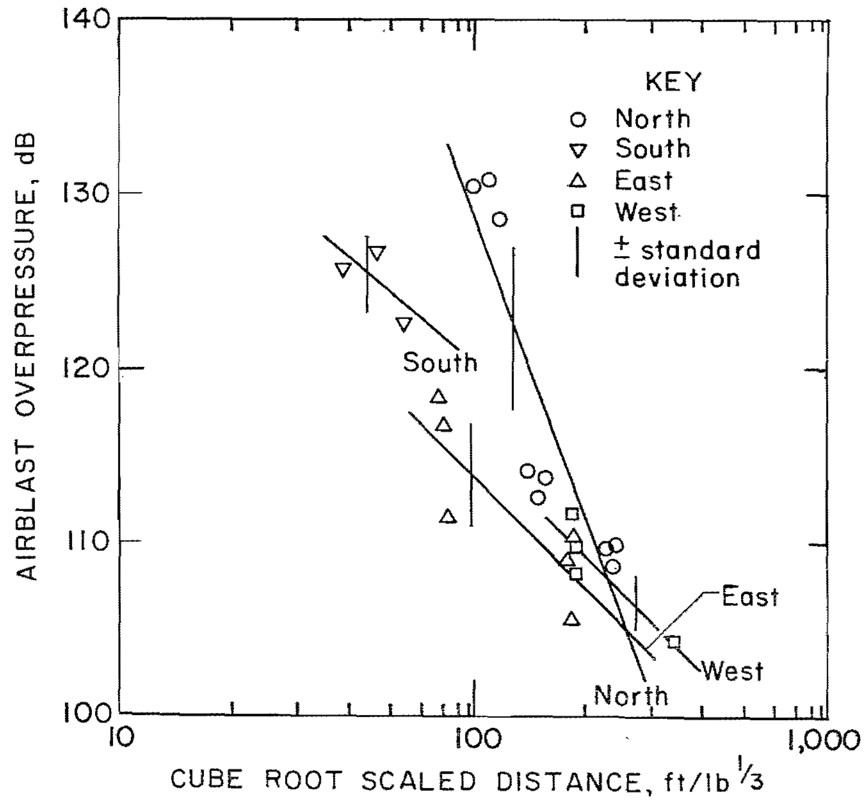

FIGURE 32. - Propagation plot of peak airblast for 23- by 45-ft burden and spacing array with 100- by 17-ms timing, shots 50-52.

DIRECTIONAL EFFECTS

Wiss (15) has shown that direction of initiation affects the magnitude of ground vibration levels. However, he used only one seismograph instrument array for each shot, with a different direction chosen for several similar shots.

The blast design examined for this report was the normal one used by the mine. Delays of 17 ms were used between holes in the echelons. A delay time of 42 ms was used between echelons. Actual delay times are shown in table 2 as shots 14-23.

The ground vibration data are shown as a propagation plot in figure 33. The airblast data are presented in figure 34. A least-squares regression analysis was used to determine the regression line of each set of data. The slopes and intercepts for each line are shown in table 5. Analysis of variance tests were performed on the data to determine if one regression line could be used to represent all the data, and if not, if all the regression lines had a common slope.

Analysis of the ground vibration data shows that the intercepts of the regression lines are significantly different, and thus the vibration levels are affected by the orientation of the shot. The slope of the lines was only marginally significantly different. The slope of the line associated with the data from the seismograph array in the western direction is less than that of the others, implying less attenuation in this as-yet-undisturbed ground. The analysis of variance was performed on the other three directions, and it was found that there was no significant difference in the slope of the regression lines. Therefore, it was felt that the data can be represented by four regression lines with a common slope (fig. 35). This indicates that the vibration level is dependent on direction from the blast, but attenuation of the vibrations is independent of direction with the possible exception of the western direction. This may be due to a geologic anomaly west of the mine. The western part of the mine is overlain by lacustrine and sand and gravel deposits associated with a large creek bed drainage area (fig. 2). This tended to produce lower predominate frequencies of ground vibrations (fig. 36) in the transverse axis than for the other arrays on undisturbed ground (north and south directions). Frequencies of vertical and radial vibrations did not appear to be affected. The frequency of vibrations in the reclaimed spoil or eastern direction was also predominately lower.

A frequency effect was found to be associated with the direction of the progressing free face. This is the effective burden direction and is perpendicular to the spacing or row of holes. For example, in the typical blast layout of figure 4, the initiation direction from hole to hole in a row is northwest, or to the upper left. However, the free face is progressing southward, or for this echelon pattern, to the southwest.

In the direction of the progressing free face, the spectral spread is wide and includes higher frequencies such as that corresponding to the interspacing timing. For example, shots 30 and 31 had spacing or between-hole delay intervals averaging 22 to 25 ms and showed a prominent 40-Hz spectral component in the progressing face direction. These high frequencies were present even at the farthest stations. In the opposite direction, however, the higher frequencies were absent and the narrow spectra are almost all low frequency (10 to 20 Hz). The geometry of the seismic wave travel path could be partly responsible, with blasted material being a poor conducting medium for the high-frequency seismic energy.

The highest vibration levels were found in the western direction, with levels in the north array direction the next highest. Direction of initiation was in the northwest direction, as is consistent with the results of Wiss. The results in figure 35 suggest that vibration levels in the direction of initiation can be double those in the opposite direction.

EFFECTS OF BLASTHOLE ARRAY SIZE

Three blasthole layout array sizes were used for 42- by 17-ms timing delays, as shown in tables 1 and 2 (shots 14-36).

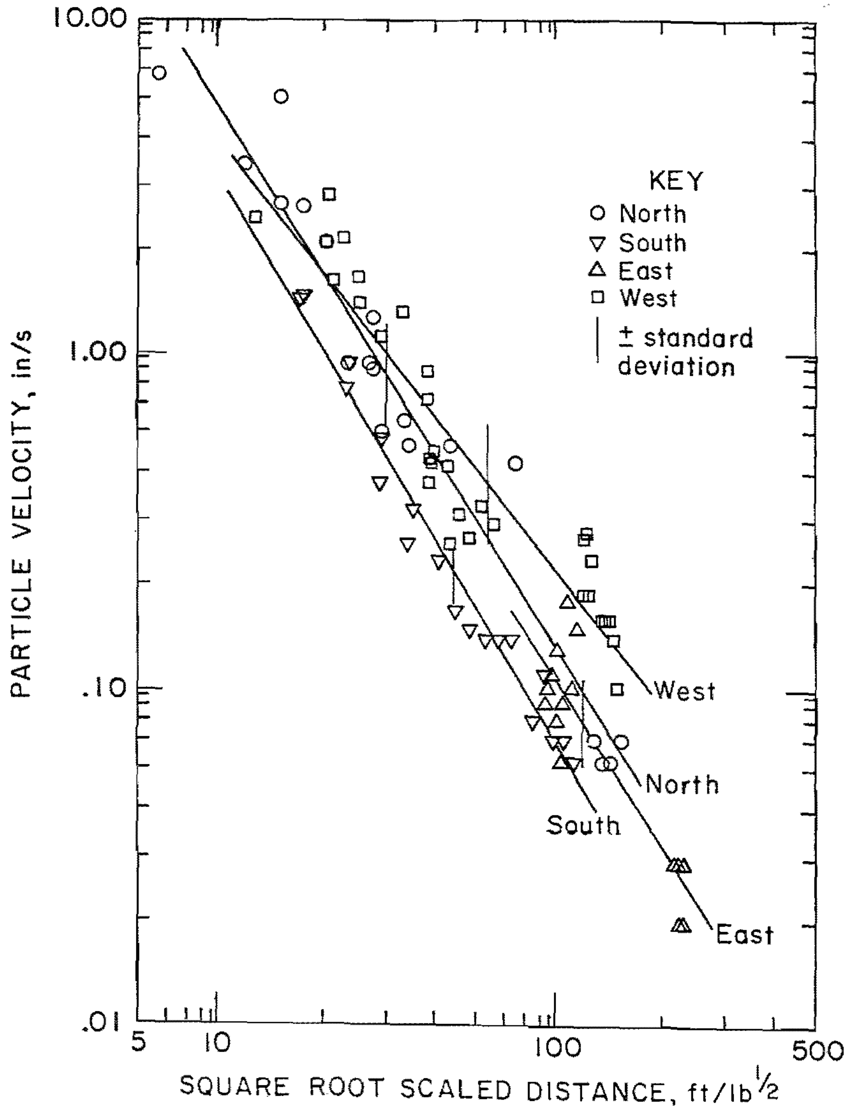

FIGURE 33. - Propagation plot of peak particle velocity for 21- by 42-ft burden and spacing array with 42- by 17-ms timing, shots 14-23.

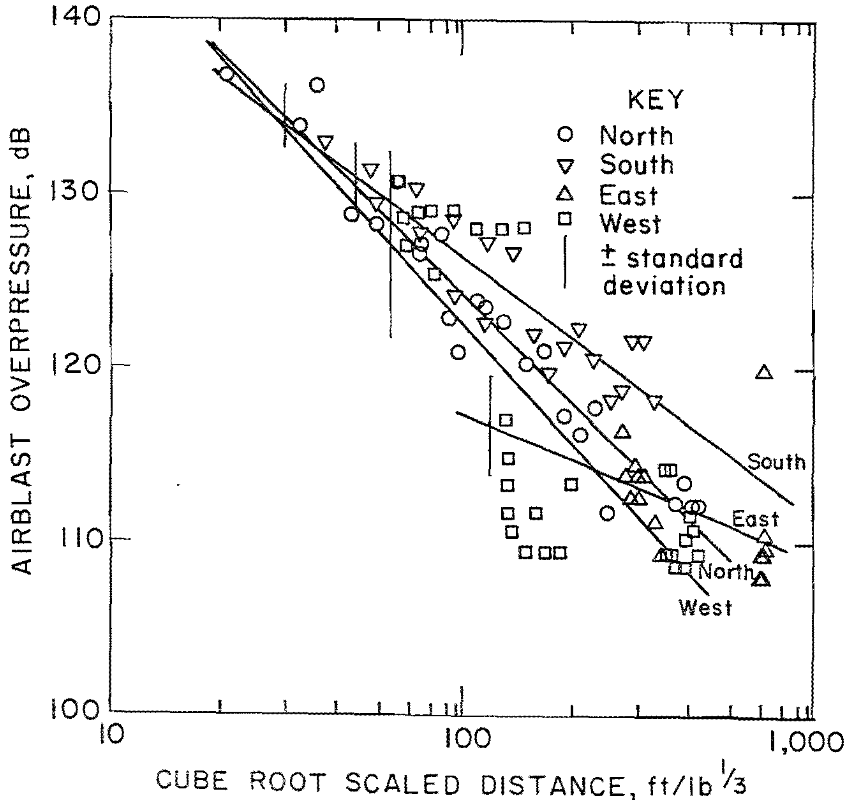

FIGURE 34. - Propagation plot of peak airblast for 21- by 42-ft burden and spacing array with 42- by 17-ms timing, shots 14-23.

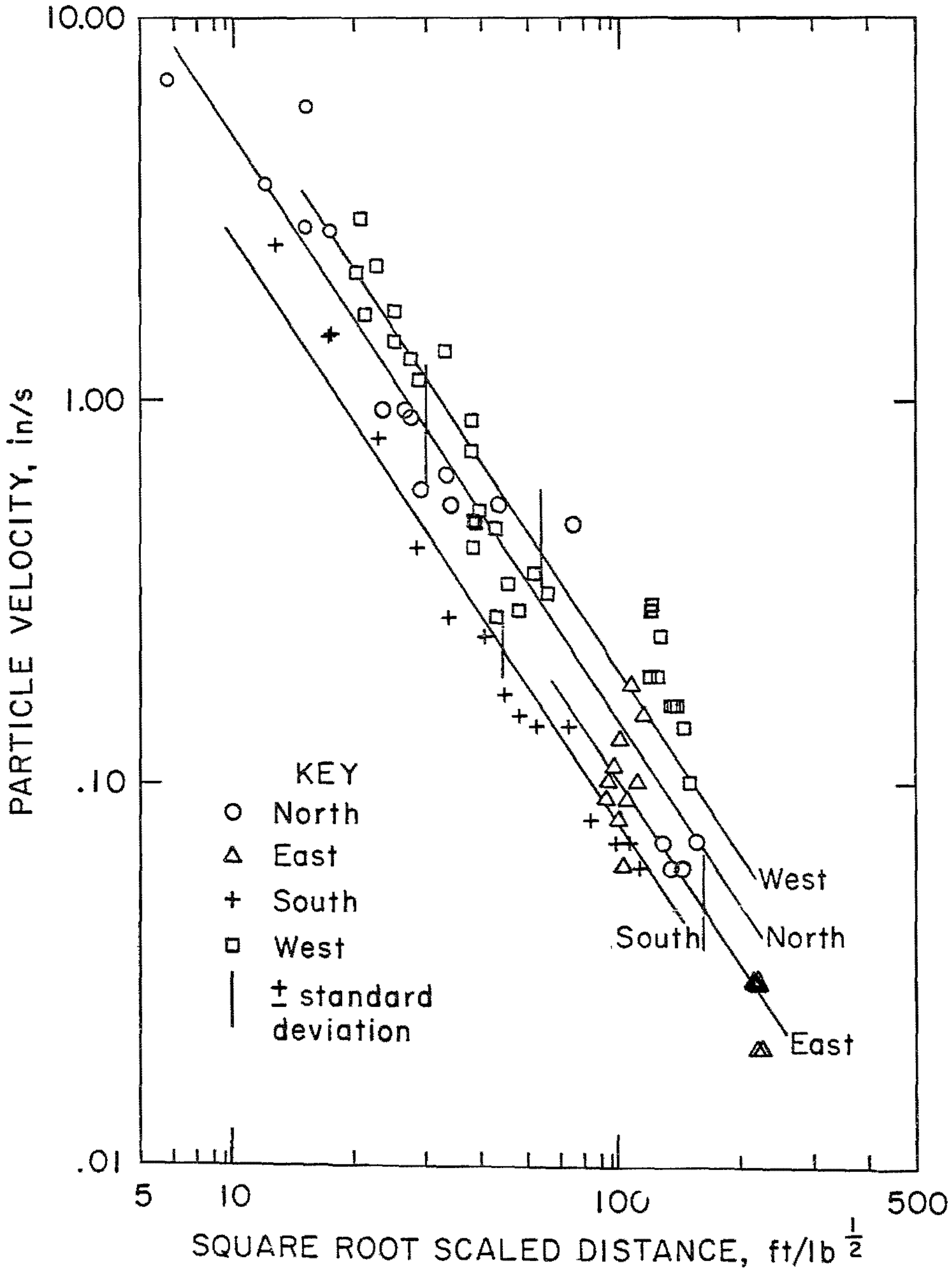

FIGURE 35. - Directional effects on propagation of ground vibrations.

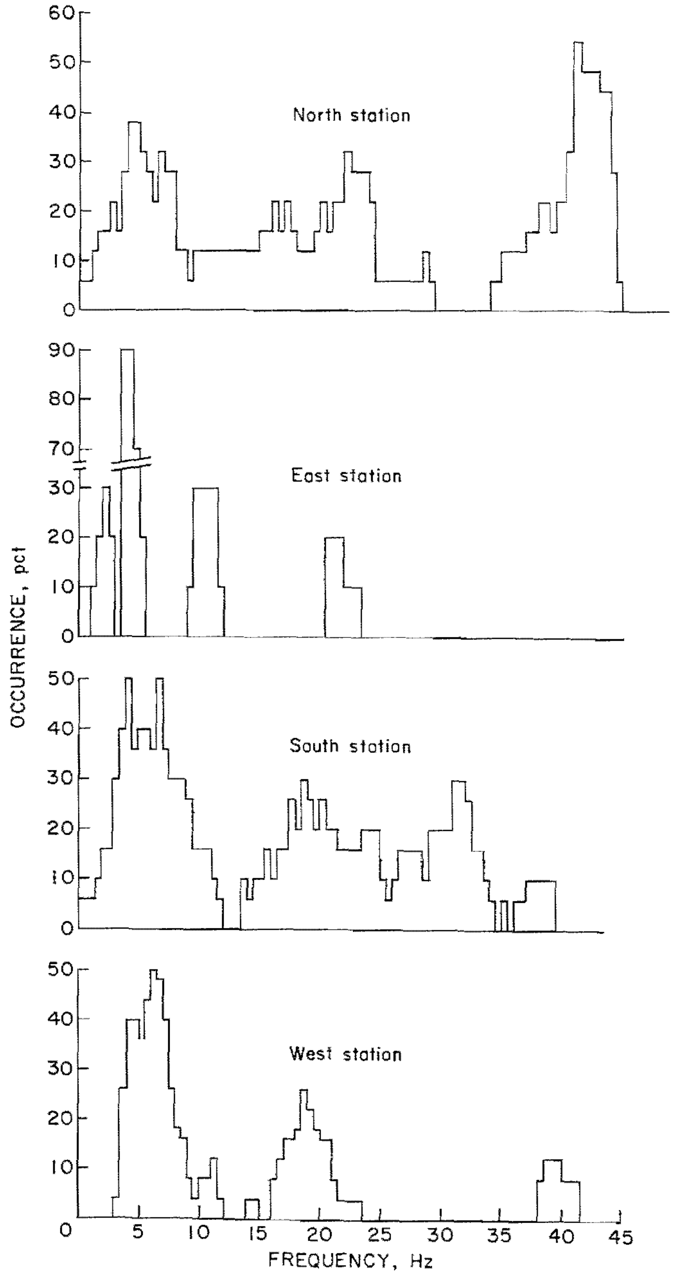

FIGURE 36. - Predominate frequencies of transverse ground vibrations.

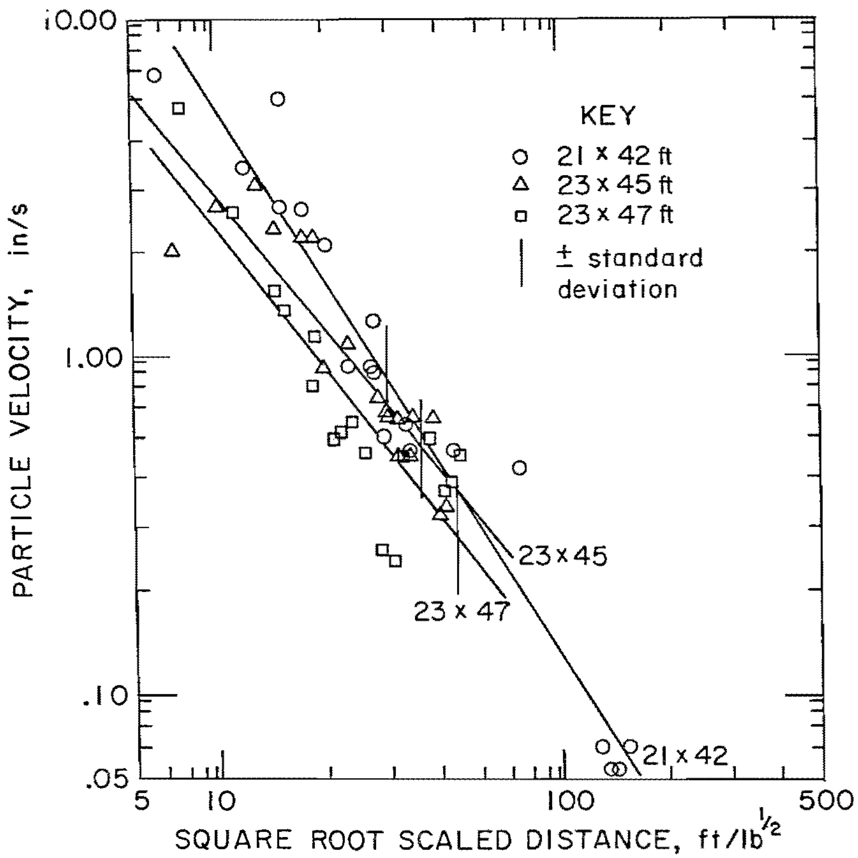

FIGURE 37. - Propagation plot of peak particle velocity for three array sizes with 42- by 17-ms timing, shots 14-36, north direction.

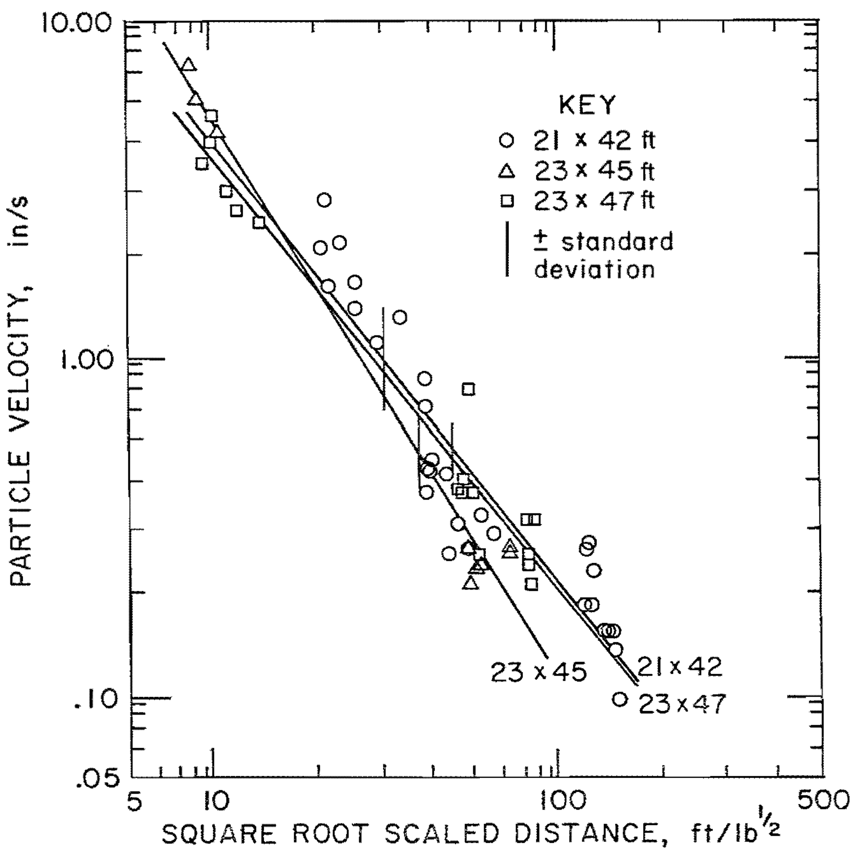

FIGURE 38. - Propagation plot of peak particle velocity for three array sizes with 42- by 17-ms timing, shots 14-36, west direction.

Although the sizes differ by only a few feet, the largest array represents 23 pct more rock than the smallest. Results are shown in figures 37 and 38 as propagations in the north and west directions. Generally, the smaller or tighter arrays produced higher particle velocities. This could be seen at close range. At scale distances of 40 or more, however, increased scatter gave more mixed results. Here differences in propagation have presumably overwhelmed the small advantage of increased layout size.

Theory predicts a higher vibration level per hole for a large blasthole layout array, for a constant amount of explosive per hole, because of the larger burdens on each blasthole. This experiment found the reverse to be true. Most likely, the shot layout had not yet reached a size where overburdening begins, or the optimum powder factor. At some array size larger than studied here, the rock will be poorly fragmented and excess energy will go into ground vibrations.

CONCLUSIONS

Careful attention to blast design practices can help reduce airblast and ground vibrations generated by mine blasting. This study examined blasthole delay intervals and their effects on airblast and vibrations.

Airblast was influenced by the trace velocity along the free face. The trace velocity, which is a function of delay interval and spacing between holes in an echelon, should be chosen to be less than the speed of sound in air. Airblast was reduced by about 6 dB by choosing delays giving a trace velocity of 80 pct of the speed of sound rather than a supersonic velocity.

Delays between holes in each row or echelon should be greater than 1 ms per foot of spacing, in order to prevent reinforcing of the airblast wave fronts from the individual holes. Care must also be taken to avoid selection of delay intervals that can cause airblast frequencies equal to the natural frequencies of midwalls of nearby structures (about 11 to 25 Hz). Delay intervals of less than 40 ms will usually not present a problem.

Orientation of the blast and direction of initiation had a noticeable effect on the magnitude of vibrations. Vibration levels in the direction of initiation were about twice the level of those away from the direction of initiation. Vibration levels across the pit from the blast were also lower.

Vibration levels were also dependent on the delay interval between rows. Adequate time must be provided for burden relief for each row. This investigation found that the delay interval between rows should be as long as practical for the burden involved. The longest burden relief value of 4.3 ms/ft gave the lowest vibration levels. This is also consistent with good fragmentation results as reported by Winzer (10, 17) and Andrews (13).

The timing of delay intervals between rows had no influence on the frequency content of the vibrations. Geology was the controlling factor for predominate frequencies of vibrations in this investigation.

Further work is needed to better understand the complex interactions between spacing, burden, and delay intervals within and between rows of blastholes and their influence on ground vibrations and airblast. Fundamental work should be done with various burden and spacing delay intervals using only two echelons. This would reduce scatter in the vibration data due to statistical variation in initiator firing times.

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APPENDIX.--AIRBLAST AND GROUND VIBRATION DATA OF PRODUCTION BLASTS

Seismograph station	Square root scaled distance	Ground vibration in/s Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 1: 9/18/80, 1125; 500 LB/DELAY, 11700 LB TOTAL EXPLOSIVE							
1 North	17.3	3.82	2.70	.80	3.82	48.8	142.3
2 North	88.5	*****	*****	*****	*****	249.5	******
3 North	190.7	.01	.02	.01	.02	537.2	117.1
1 East	23.0	1.35	1.18	.82	1.35	64.9	140.0
2 East	74.4	.11	.11	*****	.11	209.7	123.7
3 East	199.0	.02	.03	.03	.03	560.7	112.7
1 South	48.2	.25	.37	.24	.37	135.9	128.4
2 South	117.0	.05	.12	.07	.12	329.7	123.7
1 West	8.5	3.55	4.44	6.94	6.94	23.9	149.4
2 West	66.7	.16	.21	.14	.21	188.0	125.5
3 West	191.9	.03	.06	.04	.06	540.8	113.1
SHOT 2: 9/18/80, 1210; 500 LB/DELAY, 10100 LB TOTAL EXPLOSIVE							
1 North	17.0	3.83	3.73	1.38	3.83	48.0	140.6
2 North	92.8	.09	.08	.09	.09	261.6	127.7
3 North	195.0	*****	*****	*****	*****	549.3	******
1 East	21.6	.94	.95	.67	.95	60.7	136.3
2 East	74.7	.10	.11	*****	.11	210.4	123.6
3 East	199.1	.02	.03	.02	.03	560.8	108.8
1 South	44.0	.23	.37	.17	.37	123.8	128.6
2 South	112.7	.05	.09	.06	.09	317.6	121.4
1 West	8.1	2.96	6.48	4.52	6.48	22.8	150.8
2 West	66.6	.19	.20	.11	.20	187.7	127.2
3 West	191.7	.03	.08	.06	.08	540.1	116.7
SHOT 3: 9/19/80, 1110; 500 LB/DELAY, 6800 LB TOTAL EXPLOSIVE							
1 North	16.8	2.03	1.71	1.00	2.03	47.2	130.4
2 North	88.1	.09	.10	.09	.10	248.3	121.0
3 North	197.9	.02	.02	.01	.02	557.6	105.1
1 East	20.5	2.29	1.39	.75	2.29	57.8	******
2 East	74.9	.13	.08	*****	.13	211.0	119.0
3 East	198.9	.03	.02	.02	.03	560.3	107.4
1 South	39.2	.57	.40	.35	.57	110.5	122.8
2 South	107.9	.06	.15	.06	.15	303.9	******
1 West	16.9	1.53	2.03	1.04	2.03	47.7	136.0
2 West	67.2	.15	.29	.11	.29	189.2	******
3 West	191.9	.04	.06	.02	.06	540.8	108.2
SHOT 4: 9/19/80, 1202; 300 LB/DELAY, 13500 LB TOTAL EXPLOSIVE							
1 North	24.4	1.50	.89	.68	1.50	63.2	132.8
2 North	122.2	.08	.10	.07	.10	316.1	122.3
3 North	263.9	.02	.03	.02	.03	682.8	109.2
1 East	27.8	2.38	1.91	.83	2.38	71.8	******
2 East	98.5	.16	.10	*****	.16	254.8	119.0
3 East	257.4	.03	.03	.02	.03	666.1	107.4
1 South	42.3	.70	.70	.55	.70	109.5	119.2
2 South	130.9	.12	.17	.07	.17	338.8	******
1 West	20.6	1.81	1.49	1.70	1.81	53.3	136.4
2 West	87.6	.18	.23	.13	.23	226.8	******
3 West	247.6	.04	.02	.03	.04	640.7	106.6
SHOT 5: 9/20/80, 911; 1200 LB/DELAY, 18000 LB TOTAL EXPLOSIVE							
1 North	19.2	1.69	4.00	3.47	4.00	62.8	132.8
2 North	50.1	.33	.45	.39	.45	163.2	127.0
1 East	19.3	1.19	1.11	.63	1.19	63.1	136.7
2 East	71.0	.16	.10	*****	.16	231.5	126.3
3 East	151.3	*****	.06	.04	.06	493.1	112.7
1 South	22.5	1.21	1.23	.95	1.23	73.2	128.2
2 South	53.4	.38	.78	.78	.78	174.1	111.1
1 West	7.4	9.84	4.87	3.91	9.84	24.3	141.5
2 West	25.1	*****	*****	*****	*****	81.9	******
3 West	64.4	*****	*****	*****	*****	209.9	******

Seismograph station	Square root scaled distance	Ground vibration in/s				Cube root scaled distance	Peak airblast, dB
		Vertical	Radial	Transverse	Peak		
SHOT 6: 9/20/80, 927; 1400 LB/DELAY, 24700 LB TOTAL EXPLOSIVE							
1 North	21.4	1.35	2.16	2.09	2.16	71.5	127.1
2 North	49.7	.46	.49	.34	.49	166.4	129.2
1 East	16.6	1.39	1.04	.61	1.39	55.4	136.4
2 East	64.1	.17	.11	.19	.19	214.5	127.0
3 East	138.4	*****	.06	.05	.06	463.0	115.1
1 South	17.4	1.11	2.40	1.33	2.40	58.2	131.5
2 South	46.1	.38	.80	.80	.80	154.1	110.3
1 West	7.8	6.22	4.27	9.68	9.68	26.1	139.9
2 West	22.7	.92	1.56	.97	1.56	76.0	131.6
3 West	60.1	.17	.22	.27	.27	201.1	110.7
SHOT 7: 9/20/80, 957; 1200 LB/DELAY, 30400 LB TOTAL EXPLOSIVE							
1 North	27.1	.95	1.21	1.31	1.31	88.2	127.7
2 North	57.6	.20	.24	.20	.24	187.8	124.9
1 East	17.6	1.18	1.01	.49	1.18	57.4	136.7
2 East	68.1	.19	.13	.14	.19	222.1	125.0
3 East	148.1	*****	.05	.03	.05	482.7	114.8
1 South	15.0	1.95	2.86	1.27	2.86	48.8	133.8
2 South	45.9	.39	1.02	1.02	1.02	149.7	109.2
1 West	10.6	4.17	8.01	8.01	8.01	34.5	135.0
2 West	24.5	.82	1.01	1.04	1.04	80.0	125.5
3 West	65.8	.18	.20	.28	.28	214.6	109.6
SHOT 8: 9/20/80, 1023; 1200 LB/DELAY, 49200 LB TOTAL EXPLOSIVE							
1 North	30.8	1.69	4.27	2.67	4.27	100.4	128.4
2 North	61.5	.35	.39	.59	.59	200.4	128.3
1 East	18.8	1.63	1.18	.80	1.63	61.2	142.7
2 East	68.1	.30	.14	*****	.30	222.1	134.4
3 East	147.8	*****	.10	.05	.10	481.1	121.1
1 South	11.1	4.52	5.22	6.30	6.30	36.3	141.4
2 South	42.1	.57	1.23	.56	1.23	137.1	123.9
1 West	13.0	6.04	4.09	5.57	6.04	42.3	139.6
2 West	24.0	.87	1.57	1.51	1.57	78.1	127.7
3 West	65.8	.24	.63	.63	.63	214.6	116.7
SHOT 9: 9/20/80, 1036; 1200 LB/DELAY, 15600 LB TOTAL EXPLOSIVE							
1 North	34.3	.64	1.42	.64	1.42	112.0	124.9
2 North	65.1	.24	.23	.29	.29	212.2	121.0
1 East	20.5	.97	1.08	.65	1.08	66.8	131.5
2 East	68.1	.09	.13	*****	.13	222.1	117.1
3 East	147.5	*****	.04	.04	.04	480.0	108.8
1 South	7.6	5.42	7.00	5.79	7.00	24.7	139.0
2 South	38.5	.53	.91	.32	.91	125.4	114.7
1 West	15.8	3.56	6.69	3.55	6.69	51.6	132.3
2 West	24.2	.73	.95	.96	.96	79.1	122.6
3 West	66.1	.16	.23	.19	.23	215.5	109.6
SHOT 10: 9/23/80, 1000; 1200 LB/DELAY, 20550 LB TOTAL EXPLOSIVE							
1 North	10.9	3.09	3.91	.85	3.91	35.5	134.7
2 North	34.5	.46	1.42	.59	1.42	112.5	125.8
1 East	23.4	.70	.60	.20	.70	76.2	137.1
2 East	75.8	.15	.16	*****	.16	247.1	124.1
3 East	146.9	.03	.06	.04	.06	479.0	113.4
1 South	22.8	.66	1.70	1.02	1.70	74.3	123.7
2 South	62.4	.15	.35	.21	.35	203.3	120.4
1 West	9.2	3.13	4.59	2.92	4.59	30.1	135.0
2 West	28.3	.78	1.35	.66	1.35	92.2	127.7
3 West	103.1	.09	.15	.09	.15	335.9	117.3

Seismograph station	Square root scaled distance	Ground vibration in/s: Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 11; 9/23/80, 1029; 1200 LB/DELAY, 35600 LB TOTAL EXPLOSIVE							
1 North	15.0	2.93	4.00	1.99	4.00	49.0	131.7
2 North	38.7	.46	1.09	.56	1.09	126.1	127.7
1 East	23.4	.60	.63	.29	.63	76.2	138.6
2 East	75.4	.14	.14	.22	.22	245.9	130.6
3 East	146.6	.06	.05	.08	.08	478.1	116.5
1 South	18.5	1.35	2.36	1.47	2.36	60.2	133.0
2 South	58.0	.35	.67	.67	.67	189.2	121.2
1 West	8.9	6.04	4.08	4.09	6.04	29.2	138.7
2 West	26.0	1.06	1.28	1.08	1.28	84.7	128.2
3 West	102.2	.14	.22	.18	.22	333.1	112.7
SHOT 12; 9/23/80, 1045; 1200 LB/DELAY, 36500 LB TOTAL EXPLOSIVE							
1 North	18.8	1.42	1.24	.55	1.42	61.2	133.7
2 North	42.3	.29	.68	.26	.68	138.1	124.9
1 East	24.0	.51	.57	.21	.57	78.1	134.9
2 East	75.5	.07	.12	*****	.12	246.0	119.0
3 East	146.6	.06	.08	.03	.08	478.1	114.5
1 South	14.7	1.04	2.54	1.53	2.54	48.0	129.7
2 South	54.3	.24	.29	.18	.29	176.9	125.3
1 West	10.1	4.09	3.73	5.79	5.79	32.9	138.4
2 West	24.2	1.04	1.85	.68	1.85	79.1	128.2
3 West	101.3	.11	.12	.08	.12	330.3	112.7
SHOT 13; 9/23/80, 1103; 1900 LB/DELAY, 36900 LB TOTAL EXPLOSIVE							
1 North	18.4	1.42	1.82	.64	1.82	64.9	130.9
2 North	37.2	.36	.71	.33	.71	130.8	127.3
1 East	20.4	.55	.54	.21	.55	71.9	138.2
2 East	60.2	.15	.19	.18	.19	211.9	125.0
3 East	116.5	.06	.08	.05	.08	410.2	112.7
1 South	8.3	2.71	5.88	2.78	5.88	29.1	139.5
2 South	39.7	.32	.83	.83	.83	138.7	117.1
1 West	10.1	4.27	4.18	7.12	7.12	35.5	134.7
2 West	17.9	1.67	2.28	1.78	2.28	63.0	130.9
3 West	79.6	.13	.19	.16	.19	280.2	112.7
SHOT 14; 9/23/81, 936; 1000 LB/DELAY, 13700 LB TOTAL EXPLOSIVE							
1 North	15.5	2.79	2.23	2.29	2.79	48.9	128.7
2 North	28.9	.84	.89	.48	.89	91.4	122.9
1 East	115.6	.09	.15	.06	.15	365.5	109.3
2 East	232.3	.03	.03	.03	.03	734.7	109.5
1 South	13.1	2.19	2.52	1.26	2.52	41.3	132.9
2 South	50.8	.10	.17	.15	.17	160.5	121.9
1 West	26.3	1.68	.86	1.17	1.68	83.1	125.4
2 West	43.0	.34	.42	.47	.47	136.1	114.8
3 West	121.1	.09	.19	.12	.19	382.9	114.2
SHOT 15; 9/23/81, 959; 1000 LB/DELAY, 16400 LB TOTAL EXPLOSIVE							
1 North	15.5	5.81	5.81	3.33	5.81	34.8	133.9
2 North	28.9	1.27	1.18	.67	1.27	75.7	126.5
1 East	112.0	.05	.10	.05	.10	354.2	111.1
2 East	230.3	.03	.02	.02	.03	728.3	110.4
1 South	18.1	1.27	1.48	.65	1.48	57.1	129.4
2 South	55.8	.11	.15	.12	.15	176.5	119.7
1 West	23.7	2.21	1.49	1.71	2.21	74.9	128.9
2 West	42.3	.26	.41	.34	.41	133.9	113.3
3 West	122.4	.07	.28	.12	.28	387.1	109.3
SHOT 16; 9/23/81, 1034; 1000 LB/DELAY, 23200 LB TOTAL EXPLOSIVE							
1 North	18.0	2.73	2.09	1.48	2.73	57.0	128.2
2 North	36.8	.33	.53	.26	.53	116.4	123.5
1 East	108.1	.06	.18	.10	.18	341.9	******
2 East	228.2	.03	.03	.02	.03	721.7	119.9
1 South	24.0	.50	.79	.58	.79	76.0	127.0
2 South	61.9	.09	.14	.06	.14	195.9	121.2
1 West	21.5	2.95	2.86	1.56	2.95	68.0	128.5
2 West	42.0	.36	.73	.43	.73	132.9	117.1
3 West	124.0	.04	.29	.14	.29	392.2	114.2

Seismograph station	Square root scaled distance	Ground vibration in/s: Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 17: 9/23/81, 1108; 1000 LB/DELAY, 23100 LB TOTAL EXPLOSIVE							
1 North	12.2	3.64	3.27	3.33	3.64	38.6	136.2
2 North	30.7	.49	.58	.32	.58	97.1	120.9
1 East	104.4	.06	.09	.05	.09	330.2	113.8
2 East	226.4	.03	.03	.02	.03	715.8	107.9
1 South	30.2	.32	.34	.41	.41	95.4	124.2
2 South	68.1	.10	.14	.06	.14	215.5	122.3
1 West	20.9	2.13	2.09	1.37	2.13	66.2	130.7
2 West	42.6	.30	.48	.33	.48	134.6	111.6
3 West	125.9	.06	.19	.10	.19	398.1	109.3
SHOT 18: 9/23/81, 1136; 1000 LB/DELAY, 22500 LB TOTAL EXPLOSIVE							
1 North	6.8	6.82	6.14	5.95	6.82	21.4	136.8
2 North	24.3	.93	.91	.62	.93	76.9	127.1
1 East	100.9	.09	.13	.07	.13	319.2	112.5
2 East	224.7	.03	.03	.02	.03	710.5	107.9
1 South	36.6	.24	.27	.22	.27	115.8	122.5
2 South	74.7	.07	.14	.06	.14	236.1	120.5
1 West	22.1	1.33	1.65	1.54	1.65	69.8	127.0
2 West	43.9	.26	.45	.51	.51	138.9	110.6
3 West	128.0	.06	.24	.14	.24	404.8	108.7
SHOT 19: 9/25/81, 951; 900 LB/DELAY, 19200 LB TOTAL EXPLOSIVE							
1 North	76.4	.47	.30	.26	.47	151.7	120.3
2 North	109.3	*****	*****	*****	*****	259.0	111.7
1 East	103.0	.06	.06	.05	.06	319.9	113.8
2 East	235.1	.03	.02	.02	.03	730.5	110.4
1 South	17.7	1.46	1.32	1.07	1.46	55.0	131.3
2 South	85.3	.06	.08	.05	.08	265.2	118.2
1 West	26.4	.97	1.41	.82	1.41	81.9	129.0
2 West	48.8	.23	.27	.27	.27	151.5	109.4
3 West	137.6	.05	.16	.14	.16	427.6	108.7
SHOT 20: 9/25/81, 1030; 900 LB/DELAY, 22400 LB TOTAL EXPLOSIVE							
1 North	48.8	.53	.36	.33	.53	131.2	122.7
2 North	83.4	*****	*****	*****	*****	238.3	117.8
3 North	156.6	.07	.03	.04	.07	471.5	112.1
1 East	100.0	.05	.07	.08	.08	310.6	114.3
2 East	233.7	.02	.02	.02	.02	726.1	110.4
1 South	24.0	.75	.93	.47	.93	74.7	130.2
2 South	92.0	.06	.11	.08	.11	285.9	118.7
1 West	30.5	.75	1.12	.82	1.12	94.9	129.0
2 West	51.9	.20	.33	.28	.33	161.3	111.6
3 West	140.4	.05	.16	.12	.16	436.3	110.2
SHOT 21: 9/25/81, 1059; 900 LB/DELAY, 22400 LB TOTAL EXPLOSIVE							
1 North	35.7	.63	.30	.42	.63	110.8	123.9
2 North	70.1	*****	*****	*****	*****	217.8	116.2
3 North	145.1	.06	.05	.04	.06	451.0	112.1
1 East	97.4	.07	.11	.10	.11	302.9	112.5
2 East	232.5	.03	.02	.03	.03	722.4	109.2
1 South	30.5	.40	.55	.28	.55	94.7	128.5
2 South	98.6	.05	.07	.04	.07	306.5	121.6
1 West	35.4	.50	.90	1.33	1.33	109.9	128.0
2 West	55.5	.17	.28	.26	.28	172.6	109.4
3 West	143.4	.08	.12	.16	.16	445.5	111.5
SHOT 22: 9/25/81, 1122; 900 LB/DELAY, 25600 LB TOTAL EXPLOSIVE							
1 North	28.1	.93	.93	.83	.93	87.3	127.6
2 North	62.3	*****	*****	*****	*****	193.7	117.3
3 North	137.4	.06	.05	.03	.06	426.8	113.5
1 East	94.7	.10	.10	.07	.10	294.4	113.8
2 East	231.1	.03	.02	.02	.03	718.2	107.9
1 South	38.1	.24	.34	.33	.34	118.5	127.2
2 South	106.4	.04	.07	.05	.07	330.6	121.6
1 West	41.8	.40	.88	.78	.88	129.9	128.0
2 West	60.6	.19	.33	.35	.35	188.4	109.4
3 West	147.4	.09	.14	.13	.14	457.9	110.7

Seismograph station	Square root scaled distance	Ground vibration in/s: Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 23: 9/25/81, 1142; 900 LB/DELAY, 25000 LB TOTAL EXPLOSIVE							
1 North	21.0	2.14	1.44	1.10	2.14	65.4	130.6
2 North	55.0	*****	*****	*****	*****	171.0	121.0
3 North	130.0	.05	.07	.04	.07	404.0	112.2
1 East	92.8	.08	.09	.07	.09	288.2	116.3
2 East	230.1	.02	.02	.02	.02	715.0	109.2
1 South	45.4	.14	.24	.17	.24	141.1	126.6
2 South	113.7	.04	.06	.03	.06	353.4	118.2
1 West	48.2	.30	.46	.20	.46	149.9	128.0
2 West	65.9	.16	.25	.31	.31	204.8	113.3
3 West	151.4	.07	.09	.10	.10	470.3	109.3
SHOT 24: 8/20/82, 857; 2350 LB/DELAY, 25350 LB TOTAL EXPLOSIVE							
1 North	33.9	.41	.51	.38	.51	123.5	119.6
2 North	47.0	.13	.36	.24	.36	171.5	116.9
1 East	74.0	.06	.10	.21	.21	269.9	112.7
SHOT 25: 8/20/82, 918; 2300 LB/DELAY, 26050 LB TOTAL EXPLOSIVE							
1 North	31.6	.63	.66	.61	.66	114.7	124.0
2 North	44.9	.22	.33	.34	.34	163.1	120.9
1 East	72.6	.10	.15	.18	.18	263.8	117.2
2 East	106.9	.04	.08	.05	.08	388.5	111.5
1 South	9.9	6.31	4.49	2.92	6.31	35.8	131.2
2 South	20.0	.80	.80	.68	.80	72.5	125.6
SHOT 26: 8/20/82, 938; 2300 LB/DELAY, 18800 LB TOTAL EXPLOSIVE							
1 North	19.4	.81	2.24	1.09	2.24	70.3	******
2 North	29.7	.59	.69	.75	.75	108.0	117.6
3 North	43.0	.28	*****	*****	.65	156.4	116.0
1 East	71.1	.10	.16	.19	.19	258.3	114.2
2 East	105.7	.05	.02	.06	.06	383.9	108.1
1 South	11.7	1.24	4.22	2.28	4.22	42.4	129.9
2 South	21.8	.44	1.02	.54	1.02	79.1	126.7
3 South	34.7	.21	.31	.28	.31	125.9	118.6
SHOT 27: 8/20/82, 959; 2750 LB/DELAY, 33750 LB TOTAL EXPLOSIVE							
1 North	15.0	1.17	2.39	1.53	2.39	56.1	******
2 North	24.5	.98	1.09	.64	1.09	91.6	121.6
3 North	36.6	.25	*****	*****	.51	137.1	119.3
1 East	62.8	.09	.15	.20	.20	235.2	114.5
2 East	94.8	.04	.06	.06	.06	354.9	110.6
1 South	13.3	1.94	4.19	2.28	4.19	49.8	130.6
2 South	22.6	.48	.77	.94	.94	84.6	125.3
3 South	34.4	.35	.29	.25	.35	128.7	117.3
1 West	55.9	.25	.27	.28	.28	209.1	113.2
SHOT 28: 8/20/82, 1020; 2200 LB/DELAY, 26200 LB TOTAL EXPLOSIVE							
1 North	13.3	1.60	3.25	2.55	3.25	47.9	******
2 North	37.5	.27	.34	.66	.66	135.1	119.9
1 East	67.3	.06	.12	.22	.22	242.7	116.2
2 East	103.5	.08	.06	.06	.08	373.2	111.1
1 South	18.4	.74	1.87	1.01	1.87	66.3	129.6
2 South	28.8	.31	.34	.29	.34	103.8	124.6
3 South	42.0	.14	.30	.20	.30	151.4	117.7
1 West	10.6	4.00	4.67	2.91	4.67	38.2	125.2
2 West	60.8	.25	.15	.23	.25	219.2	113.2
3 West	73.8	.14	.26	.28	.28	266.0	111.1
SHOT 29: 8/20/82, 1037; 2250 LB/DELAY, 27700 LB TOTAL EXPLOSIVE							
1 North	10.2	1.75	2.80	2.13	2.80	37.0	******
2 North	20.7	.78	.75	.92	.92	75.0	122.9
3 North	34.1	.28	*****	*****	.65	123.6	120.7
1 East	64.4	.10	.21	.15	.21	233.2	116.8
2 East	100.6	.04	.09	.06	.09	364.1	111.3
1 South	21.0	.48	.96	.83	.96	76.1	130.0
2 South	31.3	.27	.67	.52	.67	113.4	126.2
3 South	44.4	.21	.23	.26	.26	160.6	119.2
1 West	9.2	4.67	5.81	3.36	5.81	33.4	125.5
2 West	58.5	.23	.24	.20	.24	211.7	110.4
3 West	73.7	.15	.27	.24	.27	266.7	111.3

Seismograph station	Square root scaled distance	Ground vibration in/s				Cube root scaled distance	Peak airblast, dB
		Vertical	Radial	Transverse	Peak		
SHOT 30: 8/20/82, 1053; 2300 LB/DELAY, 28500 LB TOTAL EXPLOSIVE							
1 North	7.6	1.58	2.06	1.31	2.06	27.7	129.1
2 North	18.0	1.65	2.25	1.32	2.25	65.3	127.4
3 North	31.3	.30	*****	*****	.68	113.6	125.8
1 East	61.9	.12	.22	.22	.22	224.8	121.3
2 East	98.0	.10	.10	.09	.10	356.0	116.4
1 South	23.3	.37	1.10	1.16	1.16	84.6	126.6
2 South	33.5	.34	.37	.45	.45	121.6	123.7
3 South	46.4	.27	.39	.15	.39	168.5	115.5
1 West	8.8	6.48	4.29	7.36	7.36	32.0	128.7
2 West	56.6	.22	.22	.19	.22	205.6	114.3
SHOT 31: 8/21/82, 923; 2050 LB/DELAY, 26850 LB TOTAL EXPLOSIVE							
1 North	8.0	5.47	3.89	2.25	5.47	28.6	141.8
2 North	16.0	1.38	1.31	1.08	1.38	57.1	136.6
3 North	35.1	.19	.51	.28	.51	125.1	119.0
1 East	58.3	.15	.07	.05	.15	207.7	119.0
2 East	102.9	.04	.05	.03	.05	366.8	******
1 South	29.2	.36	.54	.42	.54	103.9	124.7
2 South	37.6	.31	.38	.23	.38	134.1	122.3
3 South	47.5	.33	.56	.34	.56	169.4	115.9
1 West	12.0	2.76	1.49	1.78	2.76	42.7	126.0
2 West	59.7	.15	.27	.13	.27	212.7	******
3 West	86.9	.11	.34	.17	.34	309.8	102.2
SHOT 32: 8/21/82, 938; 2100 LB/DELAY, 26200 LB TOTAL EXPLOSIVE							
1 North	11.4	2.53	2.69	1.53	2.69	40.8	138.9
2 North	19.4	1.15	.63	.76	1.15	69.4	137.7
3 North	38.2	.23	.52	.29	.52	136.9	119.3
1 East	56.6	.14	.11	.15	.15	202.7	120.9
2 East	101.2	.04	.08	.03	.08	362.3	111.9
1 South	25.2	.50	.58	.46	.58	90.3	124.9
2 South	33.6	.35	.40	.41	.41	120.2	122.7
3 South	43.4	.32	.55	.41	.55	155.3	116.7
1 West	10.1	4.38	2.63	2.84	4.38	36.0	128.8
2 West	57.3	.24	.41	.17	.41	204.9	117.9
3 West	85.0	.13	.22	.16	.22	304.2	107.7
SHOT 33: 8/21/82, 954; 2100 LB/DELAY, 25050 LB TOTAL EXPLOSIVE							
1 North	15.0	1.14	1.57	.95	1.57	53.7	128.5
2 North	23.1	.60	.34	.31	.60	82.5	123.7
3 North	41.9	.19	.57	.18	.57	149.9	120.5
1 East	55.7	.15	.14	.17	.17	199.2	120.5
2 East	100.7	.04	.06	.04	.06	360.2	******
1 South	21.6	.68	.79	.62	.79	77.3	127.9
2 South	29.9	.53	.58	.62	.62	107.2	124.9
3 South	39.8	.41	.89	.80	.89	142.3	116.7
1 West	9.6	1.94	3.77	1.82	3.79	34.5	129.8
2 West	56.0	.25	.82	.22	.82	200.2	116.8
SHOT 34: 8/21/82, 1007; 2100 LB/DELAY, 26400 LB TOTAL EXPLOSIVE							
1 North	19.1	.80	.72	.82	.82	68.3	124.7
2 North	27.2	.29	.31	.52	.52	97.3	124.2
3 North	46.1	.22	.40	.37	.40	164.8	116.9
1 East	55.5	.15	.18	.17	.18	198.6	119.3
2 East	100.8	.06	.07	.04	.07	360.8	112.1
1 South	17.4	1.40	1.31	.79	1.40	62.3	130.0
2 South	25.8	.79	.84	.59	.84	92.2	126.0
3 South	35.6	.39	.57	.64	.64	127.3	120.2
1 West	10.2	5.24	3.73	3.53	5.24	36.4	130.7
2 West	54.1	.24	.45	.17	.45	193.5	113.2
3 West	83.5	.15	.27	.17	.27	298.9	108.2

Seismograph station	Square root scaled distance	Ground vibration in/s				Cube root scaled distance	Peak airblast, dB
		Vertical	Radial	Transverse	Peak		
SHOT 35: 8/21/82, 1019; 2100 LB/DELAY, 26550 LB TOTAL EXPLOSIVE							
1 North	22.0	.53	.57	.37	.57	78.9	130.8
2 North	30.2	.17	.27	.21	.27	107.9	120.3
3 North	49.0	.22	.43	.32	.43	175.4	116.2
1 East	55.2	.08	.11	.09	.11	197.4	120.9
2 East	100.6	.02	.06	.02	.06	360.1	114.1
1 South	14.5	1.40	1.27	1.27	1.40	51.8	131.7
2 South	22.8	.78	.82	.58	.82	81.7	127.5
3 South	32.6	.40	.60	.50	.60	116.8	120.3
1 West	11.2	2.57	2.78	3.13	3.13	42.3	123.9
2 West	53.3	.21	.41	.18	.41	190.7	117.9
3 West	83.3	.10	.25	.14	.25	298.2	109.4
SHOT 36: 8/21/82, 1032; 2150 LB/DELAY, 24950 LB TOTAL EXPLOSIVE							
1 North	24.9	.29	.64	.38	.64	89.4	124.7
2 North	32.9	.16	.25	.21	.25	118.2	122.2
3 North	51.5	.16	.51	.41	.51	185.1	117.9
1 East	54.3	.10	.12	.07	.12	194.9	125.9
1 South	11.2	1.90	2.95	1.79	2.95	40.2	133.3
2 South	19.5	.98	1.04	.83	1.04	69.9	127.7
1 West	13.9	2.19	1.83	2.55	2.55	50.1	125.5
2 West	52.1	.15	.42	.27	.42	187.2	112.4
3 West	82.4	.15	.34	.21	.34	295.9	106.5
SHOT 37: 8/24/82, 929; 2200 LB/DELAY, 16300 LB TOTAL EXPLOSIVE							
1 North	7.1	5.94	5.33	5.55	5.94	25.5	140.3
2 North	53.6	.22	.31	.18	.31	193.4	121.1
1 East	22.2	.31	.49	.24	.49	79.9	123.8
2 East	53.6	.16	.12	.13	.16	193.3	119.9
3 East	98.1	.04	.06	.03	.06	353.7	112.4
1 South	15.2	1.75	2.13	1.23	2.13	54.8	123.4
2 South	24.5	1.02	1.36	1.08	1.36	88.3	119.4
3 South	35.0	.65	.94	.80	.94	126.1	111.3
1 West	11.0	5.24	3.05	2.76	5.24	39.8	128.4
2 West	51.1	.16	.50	.30	.50	184.4	111.5
3 West	81.5	.18	.37	.19	.37	293.8	110.8
SHOT 38: 8/24/82, 945; 2150 LB/DELAY, 18650 LB TOTAL EXPLOSIVE							
1 North	9.2	4.15	3.83	2.00	4.15	33.2	136.5
2 North	56.4	.25	.27	.25	.27	202.5	119.1
1 East	23.1	.26	.39	.22	.39	83.0	123.2
2 East	54.4	.14	.11	.12	.14	195.4	117.2
3 East	99.3	.04	.06	.03	.06	356.9	109.4
1 South	13.3	1.86	2.73	1.33	2.73	47.6	128.3
2 South	22.7	.91	.86	1.19	1.19	81.4	121.7
3 South	33.2	.56	.69	.64	.69	119.5	117.0
1 West	10.6	5.33	2.82	2.25	5.33	38.0	132.8
2 West	51.4	.18	.69	.30	.69	184.7	112.8
3 West	82.4	.20	.21	.17	.21	296.0	107.9
SHOT 39: 8/24/82, 1001; 2100 LB/DELAY, 19200 LB TOTAL EXPLOSIVE							
1 North	11.5	1.96	3.92	1.64	3.92	41.0	142.2
2 North	59.2	.15	.36	.25	.36	211.7	121.7
1 East	24.3	.22	.53	.17	.53	86.9	121.6
2 East	55.3	.11	.12	.09	.12	198.0	122.9
3 East	100.7	.03	.05	.03	.05	360.4	115.1
1 South	11.3	1.71	2.88	1.78	2.88	40.4	******
2 South	20.8	1.07	.58	.73	1.07	74.5	135.9
3 South	31.5	.64	.36	.35	.64	112.8	128.8
1 West	10.5	4.10	3.81	6.18	6.18	37.7	133.1
2 West	51.8	.17	.43	.30	.43	185.2	120.0
3 West	83.4	.14	.24	.17	.24	298.4	110.6

Seismograph station	Square root scaled distance	Ground vibration in/s: Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 40: 8/24/82, 1013; 2100 LB/DELAY, 19200 LB TOTAL EXPLOSIVE							
1 North	13.7	.94	2.28	1.20	2.28	48.9	142.8
2 North	61.4	.10	.29	.19	.29	219.6	126.8
1 East	25.3	.26	.45	.13	.45	90.5	******
2 East	55.6	.12	.17	.12	.17	199.1	125.0
3 East	100.9	.03	.06	.04	.06	361.2	118.5
1 South	9.1	2.96	4.41	2.58	4.41	32.6	******
2 South	18.6	1.60	.93	.76	1.60	66.6	******
3 South	29.3	.71	.51	.54	.71	104.9	******
1 West	10.8	4.86	2.70	3.31	4.86	38.8	143.3
2 West	51.6	.23	.61	.29	.61	184.8	130.4
3 West	83.5	.17	.24	.18	.24	298.8	124.2
SHOT 41: 8/24/82, 1024; 2000 LB/DELAY, 18450 LB TOTAL EXPLOSIVE							
1 North	16.4	1.00	1.40	1.04	1.40	58.1	131.1
2 North	65.3	.18	.23	.20	.23	231.7	121.6
1 East	27.2	.34	.42	.26	.42	96.7	123.7
2 East	57.5	.20	.14	.13	.20	204.1	116.3
3 East	103.7	.05	.04	.03	.05	368.2	109.9
1 South	7.0	6.02	*****	5.04	6.02	24.9	132.2
2 South	16.7	2.04	2.21	1.26	2.21	59.4	123.3
3 South	27.7	.71	1.50	.87	1.50	98.2	115.1
1 West	11.9	1.01	2.78	4.15	4.15	42.2	132.5
2 West	52.9	.34	.41	.28	.41	187.6	113.6
3 West	85.7	.21	.28	.19	.28	304.3	107.7
SHOT 42: 8/25/82, 1016; 1800 LB/DELAY, 17450 LB TOTAL EXPLOSIVE							
1 North	9.4	2.36	4.30	3.55	4.30	32.6	133.4
2 North	51.4	.14	.31	.23	.31	179.3	119.8
1 East	30.1	.33	.46	.24	.46	105.1	129.6
2 East	61.2	.20	.19	.11	.20	213.5	124.3
3 East	109.8	.05	.08	.05	.08	382.9	115.6
1 South	16.1	1.53	1.55	1.68	1.68	56.2	129.8
2 South	46.9	.30	.29	.46	.46	163.6	116.8
1 West	13.5	2.36	2.02	1.91	2.36	47.2	132.3
2 West	90.5	.14	.25	.22	.25	315.6	114.3
SHOT 43: 8/25/82, 1029; 1700 LB/DELAY, 15500 LB TOTAL EXPLOSIVE							
1 North	12.2	1.32	3.18	1.09	3.18	42.1	136.1
2 North	55.5	.12	.22	.24	.24	191.7	118.6
1 East	32.7	.29	.45	.24	.45	112.9	128.1
2 East	63.7	.22	.16	.11	.22	220.1	121.8
3 East	113.4	.04	.08	.04	.08	391.7	113.8
1 South	14.0	2.23	1.81	2.32	2.32	48.3	132.1
2 South	45.7	.46	.36	.45	.46	157.8	115.7
1 West	15.5	1.45	1.31	1.80	1.80	53.5	132.9
2 West	93.4	.15	.25	.22	.25	322.8	112.9
SHOT 44: 8/25/82, 1043; 1750 LB/DELAY, 16850 LB TOTAL EXPLOSIVE							
1 North	14.4	1.09	2.80	.95	2.80	50.0	130.8
2 North	57.1	.11	.21	.17	.21	198.2	119.1
1 East	34.0	.30	.42	.31	.42	118.0	127.1
2 East	63.7	.22	.17	.10	.22	221.0	119.4
3 East	112.4	.04	.07	.05	.07	390.0	112.1
1 South	11.3	2.14	2.54	2.73	2.73	39.3	132.6
2 South	42.6	.47	.53	.36	.53	147.8	118.6
1 West	16.9	2.06	1.16	1.56	2.06	58.7	128.1
2 West	92.3	.21	.35	.21	.35	320.6	109.6
SHOT 45: 8/26/82, 947; 1650 LB/DELAY, 16650 LB TOTAL EXPLOSIVE							
1 North	9.6	4.11	4.11	1.96	4.11	33.1	142.2
2 North	42.8	.17	.17	.16	.17	147.2	122.6
3 North	61.2	.11	.23	.17	.23	210.4	120.2
1 East	36.9	.17	.28	.19	.28	126.7	120.2
2 East	66.6	.12	.10	.07	.12	228.8	117.2
3 East	116.4	.03	.04	.03	.04	400.1	******
1 South	20.6	.58	.90	.58	.90	70.7	123.6
2 South	61.2	.25	.27	.22	.27	210.5	108.6
1 West	13.5	1.75	1.94	.95	1.94	46.6	130.6
2 West	95.3	.14	.34	.13	.34	327.8	109.3

Seismograph station	Square root scaled distance	Ground vibration in/s: Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 46: 8/26/82, 1006; 1650 LB/DELAY, 16300 LB TOTAL EXPLOSIVE							
1 North	12.0	1.58	3.10	1.16	3.10	41.2	130.8
2 North	45.2	.15	.18	.19	.19	155.3	118.2
3 North	63.6	.08	.21	.22	.22	218.6	117.5
1 East	38.7	.18	.20	.18	.20	133.0	120.8
2 East	67.5	.14	.11	.08	.14	232.0	115.2
3 East	117.0	.03	.02	.03	.03	402.2	******
1 South	18.2	.66	1.18	.50	1.18	62.5	126.2
2 South	58.8	.09	.14	.11	.14	202.3	108.1
1 West	13.4	1.45	1.41	1.31	1.45	46.0	129.1
2 West	59.0	.15	.28	.27	.28	202.8	111.3
3 West	95.8	.14	.23	.16	.23	329.2	105.3
SHOT 47: 8/26/82, 1020; 1650 LB/DELAY, 15950 LB TOTAL EXPLOSIVE							
1 North	14.4	1.28	2.09	1.64	2.09	49.3	139.8
2 North	47.6	.17	.22	.16	.22	163.5	121.9
3 North	66.0	.14	.16	.14	.16	226.9	118.4
1 East	40.5	.19	.21	.14	.21	139.4	119.9
2 East	68.5	.16	.11	.09	.16	235.3	116.5
3 East	117.6	.03	.04	.03	.04	404.3	******
1 South	15.8	1.03	1.94	.93	1.94	54.3	129.8
2 South	56.4	.21	.26	.23	.26	194.0	113.9
1 West	13.7	1.07	1.64	2.03	2.03	47.1	130.5
2 West	59.5	.16	.31	.22	.31	204.6	111.5
3 West	96.3	.14	.35	.13	.35	331.1	104.8
SHOT 48: 8/26/82, 1035; 1400 LB/DELAY, 13950 LB TOTAL EXPLOSIVE							
1 North	18.0	.68	1.38	1.07	1.38	60.2	138.4
2 North	54.1	.11	.19	.15	.19	180.8	116.7
3 North	74.1	.10	.13	.12	.13	247.8	115.9
1 East	46.1	.18	.21	.16	.21	154.2	121.1
2 East	75.6	.09	.09	.07	.09	252.7	115.5
3 East	128.5	.02	.03	.03	.03	429.9	******
1 South	14.7	.78	1.59	.73	1.59	49.2	128.3
2 South	58.8	.21	.21	.18	.21	196.7	114.6
1 West	15.4	1.41	1.26	2.51	2.51	51.6	127.7
2 West	65.1	.11	.28	.26	.28	217.6	113.0
3 West	105.0	.10	.27	.11	.27	351.1	105.3
SHOT 49: 8/26/82, 1048; 1300 LB/DELAY, 12950 LB TOTAL EXPLOSIVE							
1 North	21.5	.60	1.27	.89	1.27	71.1	141.8
2 North	59.0	.11	.09	.10	.11	194.4	******
3 North	79.8	.13	.13	.09	.13	263.5	115.6
1 East	50.3	.19	.24	.11	.24	166.0	127.6
2 East	79.8	.10	.10	.09	.10	263.7	117.7
3 East	134.3	.03	.03	.03	.03	443.8	******
1 South	12.4	1.83	1.98	.86	1.98	40.9	143.1
2 South	58.2	.18	.30	.18	.30	192.1	133.8
1 West	17.2	1.45	1.30	1.67	1.67	56.7	141.9
2 West	68.3	.21	.23	.24	.24	225.6	131.7
3 West	109.6	.15	.21	.14	.21	362.1	125.9
SHOT 50: 8/27/82, 1152; 1950 LB/DELAY, 21100 LB TOTAL EXPLOSIVE							
1 North	33.2	.21	.28	.29	.29	117.5	128.5
2 North	45.1	.16	.17	.14	.17	159.1	113.7
3 North	70.9	.07	.11	.07	.11	250.6	109.9
1 East	22.6	.24	.34	.20	.34	79.9	122.7
2 East	54.1	.10	.12	.10	.12	191.2	114.7
3 East	95.5	.10	.07	.04	.10	337.7	******
1 South	12.1	2.10	2.92	1.70	2.92	42.8	130.1
1 West	55.1	.40	.27	.27	.40	194.6	114.2
2 West	102.0	.16	.19	.06	.19	360.6	******

Seismograph station	Square root scaled distance	Ground vibration in/s Vertical	Radial	Transverse	Peak	Cube root scaled distance	Peak airblast, dB
SHOT 51: 8/27/82, 1210; 1850 LB/DELAY, 20450 LB TOTAL EXPLOSIVE							
1 North	31.4	.28	.48	.36	.48	109.9	130.8
2 North	43.5	.28	.17	.16	.28	152.3	112.6
3 North	70.1	.10	.16	.12	.16	245.6	108.6
1 East	23.4	.28	.41	.17	.41	82.1	121.1
2 East	54.0	.13	.11	.11	.13	189.3	110.0
3 East	96.8	.08	.05	.04	.08	339.1	******
1 South	15.2	1.03	2.43	1.48	2.43	53.2	131.1
1 West	55.3	.30	.26	.22	.30	193.8	112.7
2 West	104.7	.08	.14	.14	.14	367.0	******
SHOT 52: 8/27/82, 1228; 1850 LB/DELAY, 20150 LB TOTAL EXPLOSIVE							
1 North	28.4	.37	.57	.55	.57	99.4	130.4
2 North	40.5	.21	.18	.22	.22	141.8	114.1
3 North	67.2	.09	.15	.15	.15	235.3	109.7
1 East	24.1	.27	.30	.17	.30	84.4	115.8
2 East	52.5	.13	.12	.13	.13	184.1	113.4
3 East	95.4	.10	.07	.03	.10	334.4	******
1 South	18.2	.99	1.12	.90	1.12	63.6	127.0
1 West	54.1	.18	.24	.20	.24	189.6	116.1
2 West	104.8	.09	.15	.08	.15	367.1	108.8

***** Data not available.

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